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Reactivation of Granular Carbon in an Infrared Traveling Belt Furnace

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REACTIVATION OF GRANULAR CARBON IN AN INFRARED TRAVELING BELT FURNACE

by

Ramin Nur
Robert W. Horvath

County Sanitation Districts of Los Angeles County
Whittier, California 90607

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Project Officer

Irwin J. Kugelman
Wastewater Research Division
Water Engineering Research Laboratory
Cincinnati, OH 45268

WATER ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
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16. ABSTRACT

An all-electrical Shirco carbon regeneration furnace and its air pollution control system have been evaluated for cost and process effectiveness in carbon reactivation at the Pomona Advanced Wastewater Treatment Research Facility. The granular activated carbon used for the Shirco Furnace evaluation study was exhausted in three 1.8 m (6 ft) diameter steel carbon adsorption columns connected in series. The columns treated unchlorinated and unfiltered activated sludge effluent from the 0.44 m^3/sec (10 MGD) Pomona Water Reclamation Plant. The Shirco carbon regeneration system was found to be as effective as the multiple hearth and rotary kiln furnaces in reactivating the exhausted granular activated carbon. The Shirco furnace required less operational skill but more maintenance labor than the multiple hearth and rotary kiln furnaces. A cost estimate based on a typical regeneration capacity of 182 kg/hr (400 lb/hr) has been made for the Shirco furnace regeneration system. Comparison of this cost estimate to those which were reported for multiple hearth and rotary kiln furnaces indicates that capital cost for the Shirco furnace is lower than that of the multiple hearth furnace and higher than that of the rotary kiln regeneration unit. The operation and maintenance cost for the Shirco furnace was, however, found to be higher than those for both the multiple hearth and the rotary kiln furnaces. The overall process cost for the Shirco furnace system based on the operation and maintenance of the pilot unit was estimated to be 61.8 cents/kg (30.9 cents/lb) for the carbon regenerated.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing muncipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researchers and the user community.

The project described in this report evaluates an all-electrical Shirco carbon regeneration furnace and its air pollution control system for regeneration of granular activated carbon used to treat activated sludge effluent. Process costs for the Shirco furnace are compared to those for a multiple hearth regeneration furnace and a rotary kiln regeneration unit.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

An all-electrical Shirco carbon regeneration furnace and its air pollution control system have been evaluated for cost and process effectiveness in carbon reactivation at the Pomona Advanced Wastewater Treatment Research Facility. The pilot scale Shirco furnace was operated within the range of 102 kg/day (224 lb/day) to 195 kg/day (434 lb/day).

The granular activated carbon used for the Shirco Furnace evaluation study was exhausted in three 1.8 m (6 ft) diameter steel carbon adsorption columns connected in series. The columns treated unchlorinated and unfiltered activated sludge effluent from the 0.44 m^3/sec (10 MGD) Pomona Water Reclamation Plant. The carbon adsorption columns provided a total of 30 minutes empty-bed detention time at a flow rate of 6.2 l/sec (100 gpm).

The Shirco carbon regeneration system was found to be as effective as the multiple hearth and rotary kiln furnaces in reactivating the exhausted granular activated carbon. The Shirco furnace required less operational skill but more maintenance labor than the multiple hearth or rotary kiln furnaces. The high maintenance requirement of the Shirco furnace was caused mainly by premature deterioration and breakdown of the heating elements and conveyor belt mistraction inside the furnace.

A cost estimate based on a typical regeneration capacity of 182 kg/hr (400 lb/hr) has been made for the Shirco furnace regeneration system. Comparison of this cost estimate to those which were reported for multiple hearth and rotary kiln furnaces indicates that capital cost for the Shirco furnace is lower than that of the multiple hearth furnace and higher than that of the rotary kiln regeneration unit. The operation and maintenance cost for the Shirco furnace was, however, found to be higher than those for both the multiple hearth and the rotary kiln furnaces. The overall process cost for the Shirco furnace system based on the operation and maintenance of the pilot unit was estimated to be 61.8 cents/kg (30.9 cents/lb) for the carbon regenerated.

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SECTION I

INTRODUCTION

This study was conducted to evaluate and determine the cost-effectiveness of the Shirco infrared traveling belt carbon regeneration system. It was a portion of a much larger investigation into the removal of potentially hazardous trace organics from wastewater. The overall findings of the research project on trace organics removal will be discussed in detail in another volume. This report, however, will limit itself to the operation and evaluation of the Shirco carbon regeneration system and its components.

An extensive pilot plant study on the granular activated carbon adsorption process for wastewater treatment has been jointly conducted since 1965 by the Sanitation Districts of Los Angeles County and the United States Environmental Protection Agency. The studies have been conducted at the Sanitation Districts' Pomona Advanced Wastewater Treatment Research Facility in Pomona, California. Initially, the Pomona carbon study utilized a multiple hearth furnace system for carbon regeneration during the first ten years of pilot plant operations. During this period, the study concerned itself with the evaluation of the various treatment process parameters, mainly pretreatment requirements, carbon characteristics, hydraulic loading rates, adsorption capacity, backwash requirement, and mode of regeneration. Different types of carbon regeneration furnaces were not evaluated, since during that initial period the multiple hearth furnace system was found to be very effective and reliable in regenerating the spent activated carbon in wastewater treatment processing. (1,2,3,4)

However, because carbon regeneration is a major factor in the cost of activated carbon treatment, investigation of other regeneration systems was deemed desirable. A study at this site with a rotary kiln (a less capital intensive process), was reported previously (7). An investigation of the Shirco furnace was conducted because it uses a different method of contacting the heated regenerant gases with the carbon which could yield lower loss of carbon during the regeneration cycle. In addition, the Shirco furnace uses electricity for heat production which may be advantageous in certain locations.

Granular activated carbon (Filtrasorb 300) was exhausted by exposure to secondary effluent in a downflow carbon contactor and then regenerated in the Shirco regeneration furnace. The performance of the carbon after regeneration was evaluated by its adsorption capacity and efficiency in the next adsorption cycle. This process was repeated for several cycles, and after each regeneration carbon quality was compared to that of its virgin state. The performance of the electric Shirco furnace was compared to that of the multiple hearth and the rotary kiln furnaces which were utilized in the past in regenerating the same type of carbon from the same carbon contactors and exposed to the same activated sludge plant effluent.

The ability to regenerate carbon to its pre-exhausted conditions, the ease of control and operation, the extent of carbon losses, and energy consumption were the basis of this evaluation.

SECTION II

CONCLUSIONS

The following conclusions can be drawn from the pilot plant study of the Shirco regeneration furnace and its comparison to the multiple hearth and/or rotary kiln furnaces:

- The all electric Shirco furnace was found to be as effective as the multiple hearth and rotary kiln furnaces in reactivating granular activated carbon which had been exhausted by an activated sludge plant effluent.

- The Shirco furnace is insulated with a thermal-shock-resistant ceramic fiber blanket. Unlike the multiple hearth furnace's refractory lining, this type of insulation was able to withstand rapid start-up and shut-down.

- The auxiliary process steam used for the multiple hearth and rotary kiln furnaces was not required for the Shirco furnace, since in the Shirco furnace the steam generated in the drying zone moves co-currently with the carbon to aid the activation process.

- The Shirco furnace system required less operational skill but more maintenance labor than the multiple hearth and rotary kiln furnaces.

- The usable life span of the Shirco furnace components such as heating elements and the conveyor belt was found to be much shorter than expected.

- The energy cost per pound of carbon regenerated by the Shirco furnace was found to be higher than the two other furnaces studied previously. This is due to the higher cost of electricity to generate the same amount of heat energy produced by fossil fuel for the multiple hearth furnace.

- All three regeneration furnace systems required an afterburner and a venturi wet scrubber for effective emission control of air pollutants. However, since no fossil fuel is used in the Shirco furnace, the total exhaust gas volume was less.

- The average carbon loss for the Shirco furnace was slightly higher than 7 percent which was reported for the multiple hearth and rotary kiln furnaces.

- The total capital cost of the Shirco furnace is estimated to be lower than the multiple hearth furnace and higher than the rotary kiln system. The total process or operation and maintenance cost for regeneration of carbon by the Shirco furnace was, however, higher than the other regeneration systems studied previously.

SECTION III

RECOMMENDATIONS

Evaluation of a more efficient Shirco furnace with the following modifications is recommended:

1) A better carbon feed system by using a different type of screw conveyor.

2) A different type of heating element or heat generating system is needed to provide longer operating life, and to cut down on maintenance time.

3) A more corrosion resistant conveyor belt with a better guidance system to prevent mistraction of the belt during carbon regeneration.

4) The duct system carrying the exhaust gases from the furnace to the afterburner should also be insulated externally to prevent excess heat loss into the atmosphere.

It is also important to investigate the Shirco furnace under a steady operation of 24 hours a day for an extended period. This continuous carbon regeneration will produce a set of data which is more suitable for comparison with other carbon regeneration systems that have been studied previously.

SECTION IV

PILOT PLANT DESCRIPTION

The 6.2 l/sec (100 gpm) pilot plant system is shown in Figure 1. The pilot plant basically consisted of three steel carbon contacting columns, a carbon dewatering and regeneration system, and the air pollution control system consisting of an afterburner and venturi scrubber.

Carbon Contacting Columns

A typical carbon contacting column used to provide the exhausted carbon for the regeneration study is shown in Figure 2. The steel columns were 1.8 m (6 ft) in diameter, and 4.9 m (16 ft) in height. The columns were operated in a downflow mode. The carbon beds were supported by a Neva Clog stainless steel screen. A surface wash piping system was provided at about 5 cm (2 in.) above the surface of the unexpanded carbon bed inside each column. The interior surface of the steel columns was coated with corrosion inhibiting bitumastic coaltar epoxy. Each column contained about 1,600 kg (3,500 lb) of Calgon Filtrasorb 300 (8x30 mesh) granular activated carbon. Characteristics of the carbon are presented in Table 1. The depth of carbon in the columns was approximately 1.5 m (60 in.), providing a nominal empty bed contact time of 10 minutes for each contactor at a flow of 6.2 l/sec (100 gpm).

Carbon Regeneration System

The infrared traveling belt carbon regeneration furnace system was manufactured by Shirco, Inc. Shirco has its headquarters in Dallas, Texas, and is owned by the Bright and Schiff partnership. The regeneration furnace is a rectangular, horizontal system consisting of an insulated enclosure through which the carbon is transported on a continuous woven wire conveyor belt. This system was assembled from a series of three modules which were bolted together prior to conveyor belt installation as shown in Figure 3 with the final dimensions of 0.81 m (32 in.) wide by 3.4 m (135 in.) long and a height of 0.86 m (34 in.). The stainless steel modules were factory lined with a thermal-shock-resistant, ceramic fiber blanket insulation system shown on Figure 4, and were equipped with support rollers for the conveyor belt. This entire unit is supported by a steel structure with the dimensions of 0.81 m (32 in.) wide by 3.4 m (135 in.) long and a height of 1.1 m (42 in.). The Shirco furnace system had a rated total regeneration capacity range of 327 kg (720 lb) to 381 kg (840 lb) of granular activated carbon per 24 hours of continuous operation.

Spent carbon is automatically released into the furnace feed hopper where it is mixed with water by means of a small (115 volt, 0.6 AMP) variable speed vibrator. The mixture of water and carbon is fed into the regenerator by a variable speed, spiral type, hollow, stainless steel screw conveyor. Inside the furnace, the wet carbon on the conveyor belt is leveled by means of an internal roller into a layer approximately 1.9 cm (3/4 in.) thick spanning 2/3 of the width of the belt. The carbon then moves through the various heating

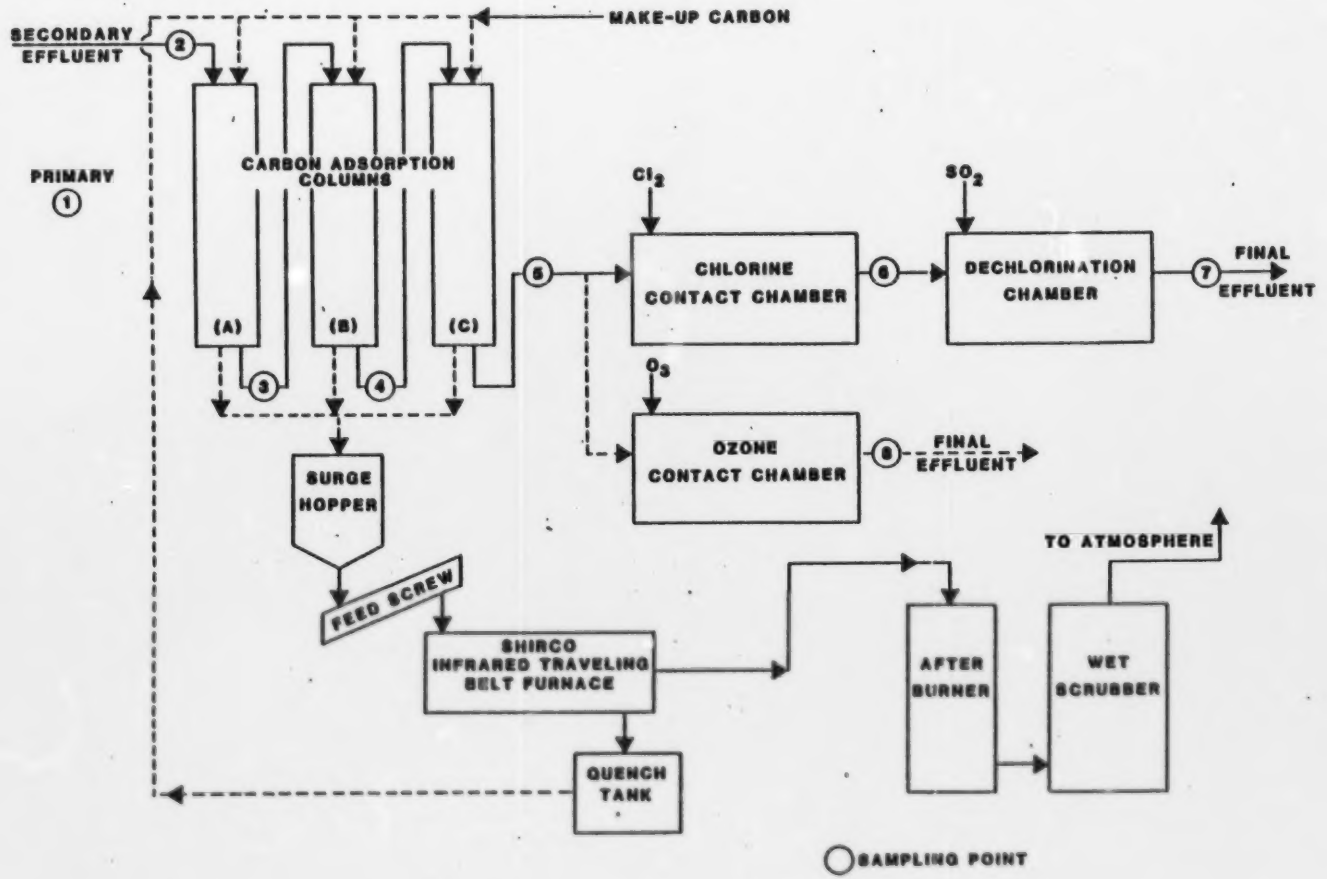
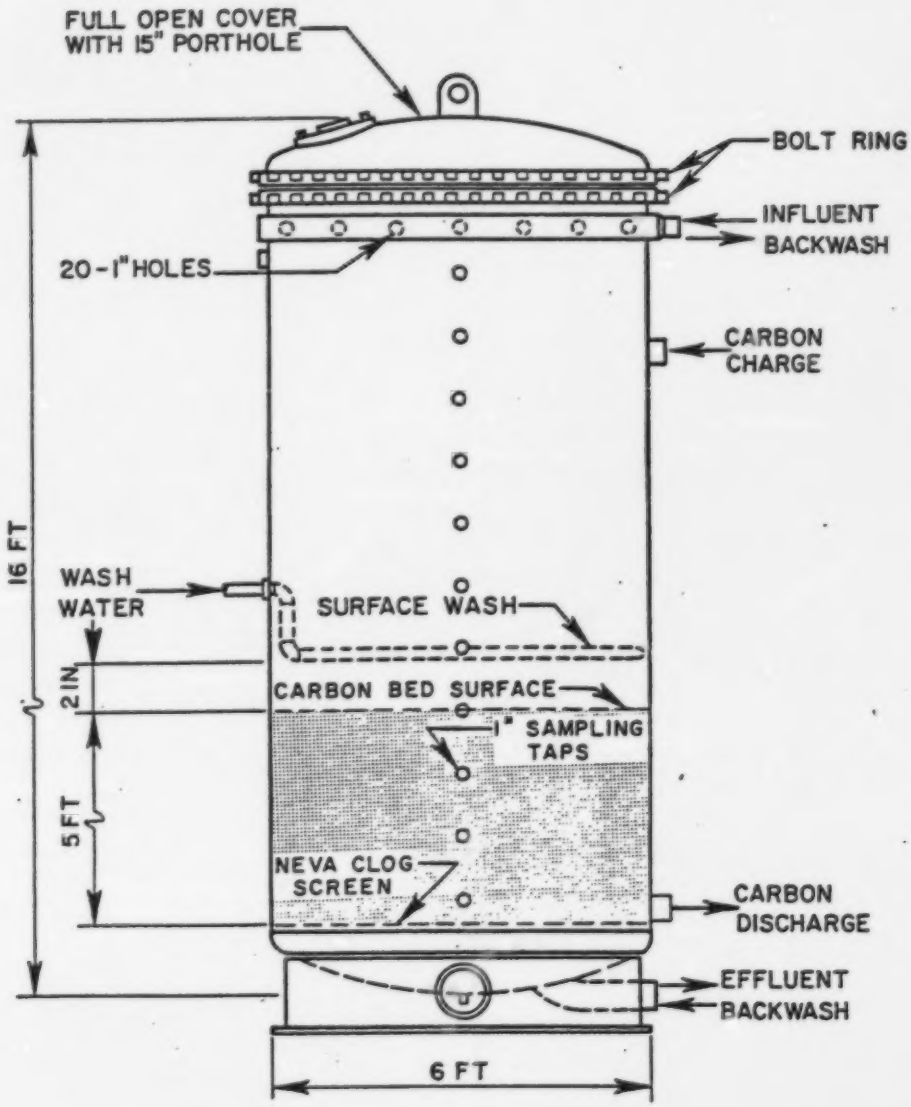


Figure 1–Schematic flow diagram of Pomona activated carbon pilot plant.



1.0 ft. = 0.305 m

Figure 2–Carbon adsorption column.

TABLE 1

Characteristics of Virgin Calgon Filtrasorb 300 Granular Activated Carbon

	Carbon Column		
	A	B	C
Apparent Density, g/cc	0.525	0.532	0.524
Iodine Number, mg/g	1079	1071	1073
Molasses Number	233	226	238
Methylene Blue Number, mg/g	261	260	261
Ash, %	6.5	6.7	6.7
Sieve Analysis:			
% retained on U.S. Sieve No.			
8	8.65	10.13	9.80
10	19.76	21.78	21.42
12	22.37	22.99	23.67
14	16.60	15.12	15.18
16	13.73	12.19	12.58
18	8.18	7.27	6.72
20	4.81	4.54	4.40
30	4.31	4.36	4.45
Pan	0.88	0.95	1.15

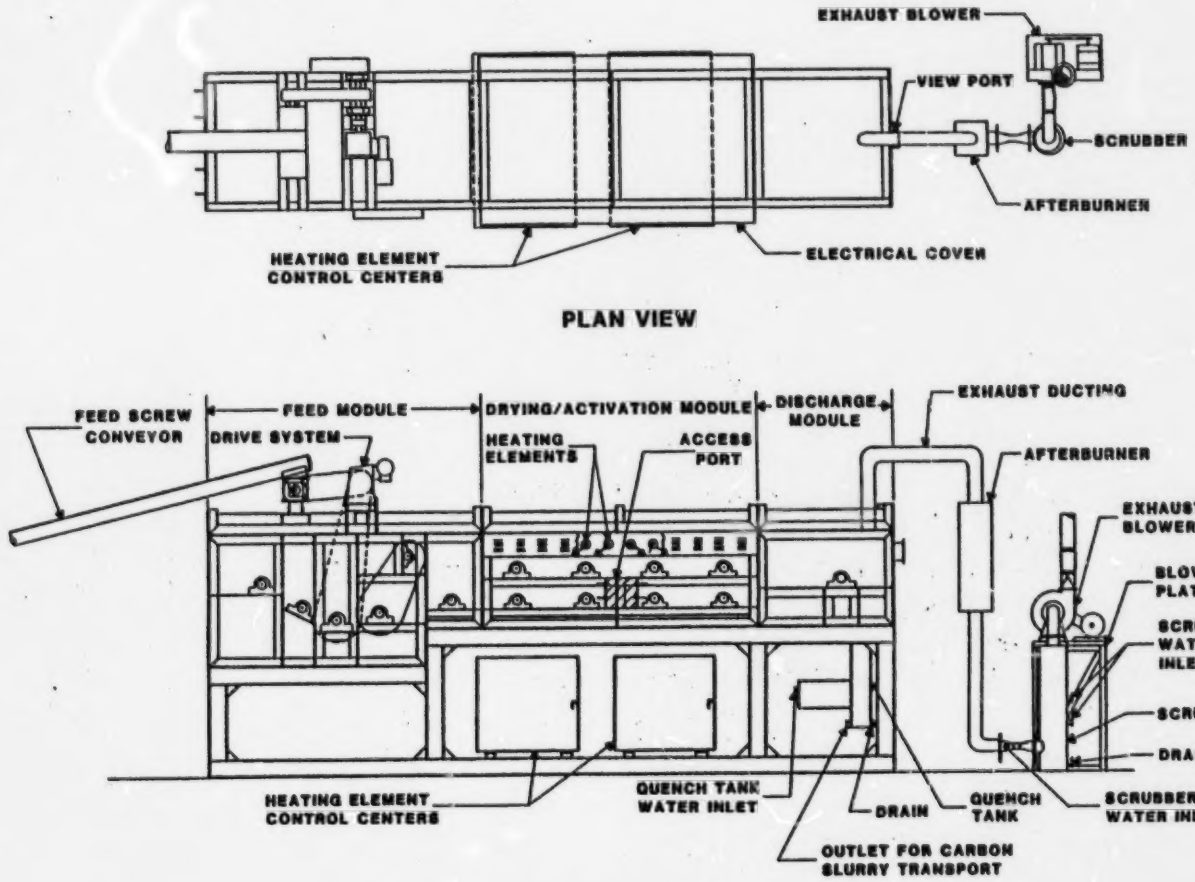


Figure 3–Shirco furnace regeneration system.

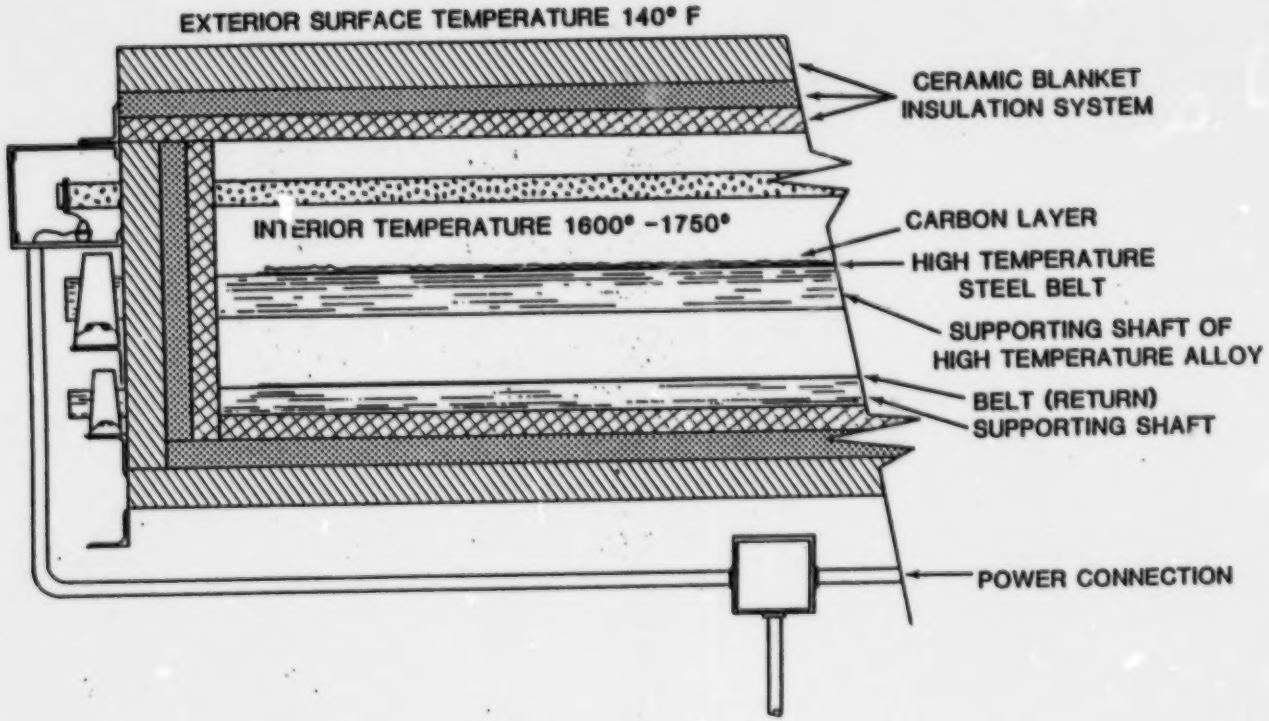


Figure 4–Cross-section of Shirco electric infrared furnace.

zones to accomplish the regeneration process. The movement of the belt inside the furnace is powered by a small variable speed 0.13 kW (1/4 HP) motor. The required regeneration temperature is provided by 24 silicon carbide heating elements located approximately 15 cm (6 in.) above the carbon layer. The regenerated carbon is then discharged at the exit end into a quench tank for cooling prior to transport to the adsorption contactors.

Three sets of thermocouples are provided along the length of the Shirco furnace for monitoring the furnace temperature profile. The first thermocouple is located 1.37 m (54 in.) from the furnace feed end and was used as a temperature indicator-controller for controlling the furnace operating temperature in the first zone (Zone A). The second thermocouple is located in the regeneration zone (Zone B), 1.27 m (50 in.) from the discharge end of furnace and it functioned as a temperature indicator-controller just as the first thermocouple in Zone A. The third thermocouple is located just ahead of the discharge point of the furnace and served only as a temperature indicator for the regenerated carbon. The temperature sensitive tips of all three thermocouples were located approximately 7.6 cm (3 in.) above the carbon layer on top of the traveling belt of the Shirco furnace.

Air Pollution Control System

The Shirco furnace is equipped with an afterburner and venturi scrubber unit for air pollution control as shown in Figures 5, 6, and 7. The exhaust gases are transferred to the afterburner unit through 6.4 m (21 ft) of duct work with an outside diameter of 30 cm (12 in.). The stainless steel duct was insulated from inside by the same type of ceramic fiber blanket that was used in the furnace, to prevent excess heat loss to the atmosphere in the process of gas transfer from the furnace to the afterburner unit. The dimensions of the rectangular afterburner were 58 cm (23 in.) wide by 66 cm (26 in.) long, and 127 cm (50 in.) in height. The entire stainless steel structure was also factory lined with thermal-shock-resistant ceramic fiber blanket insulation. The required heat energy in this unit is provided by a cluster of 12 shorter silicon carbide heating elements on the top of the unit which are shown in Figure 6 where the gases from the furnace entered the afterburner.

The exhaust temperature of the furnace is monitored by two thermocouples, one at the discharge point and the other right before the carbon exhaust enters the afterburner. An additional thermocouple is provided near the heating elements to serve as a temperature indicator-controller for controlling the afterburner operation temperature. After being cooled down to approximately 32°C (90°F) by the venturi scrubber, the burned air-exhaust mixture is dispersed into the atmosphere through a stainless steel stack by means of a 1.1 kW (1.5 HP) exhaust blower.

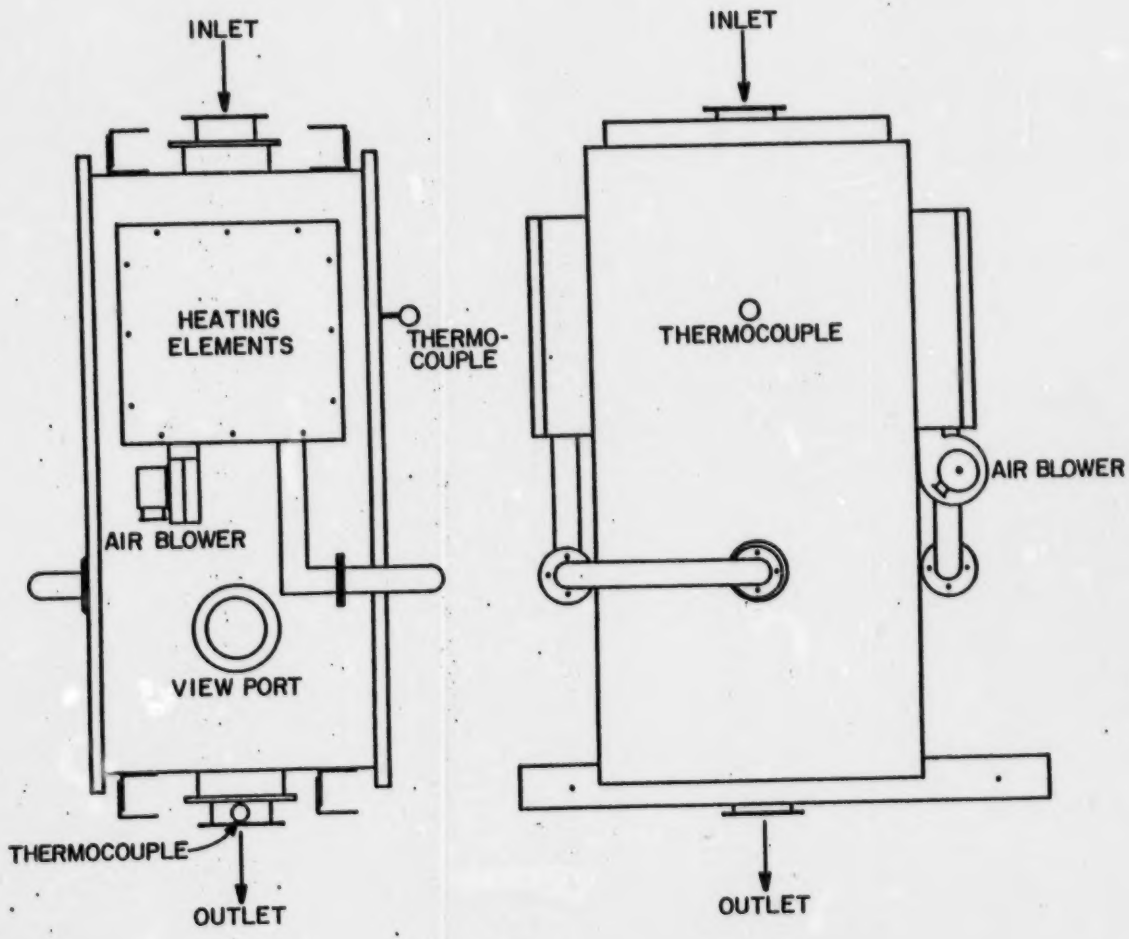


Figure 5–Front and side view of the Shirco electric afterburner.

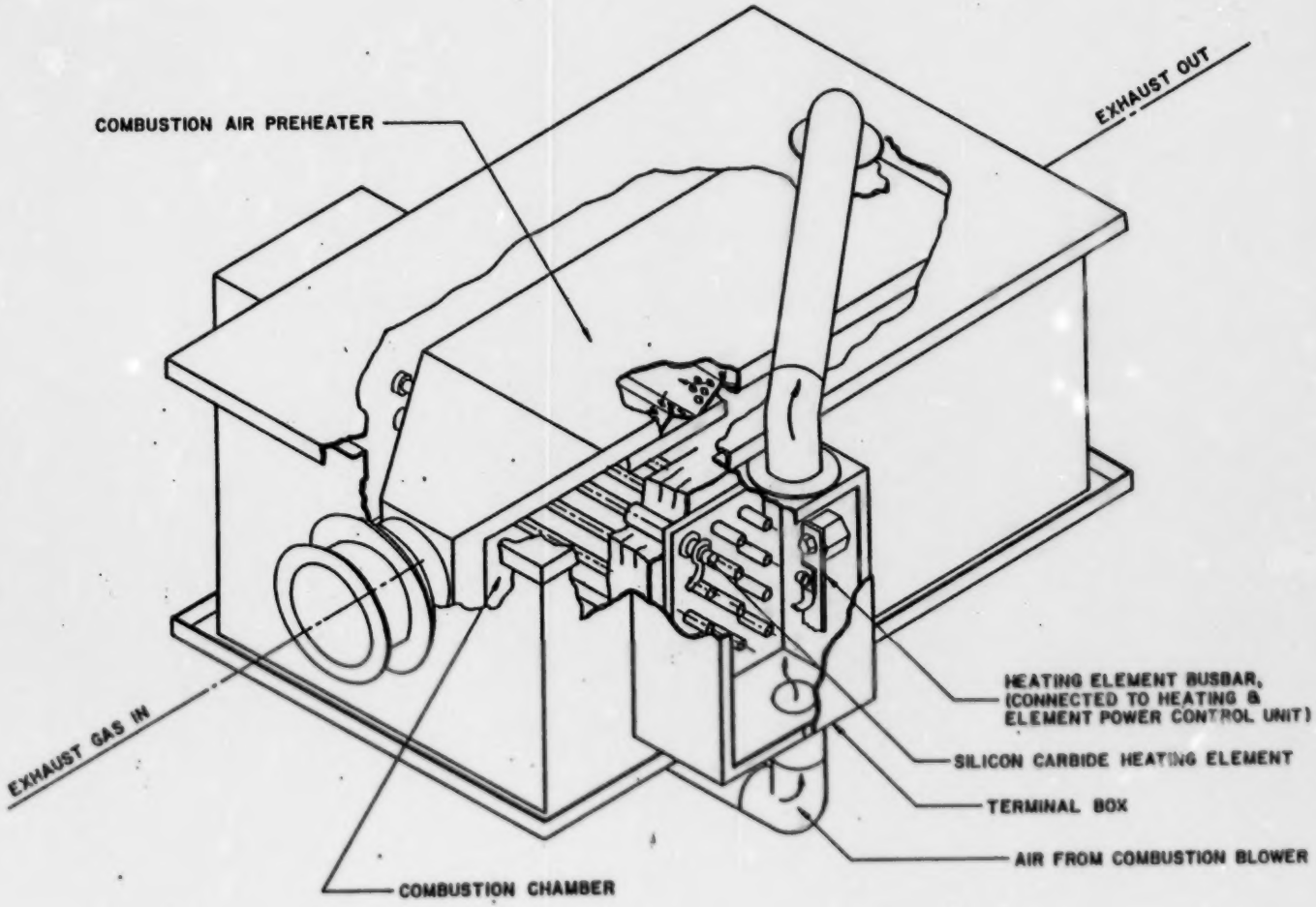


Figure 6–Internal view of the Shirco afterburner.

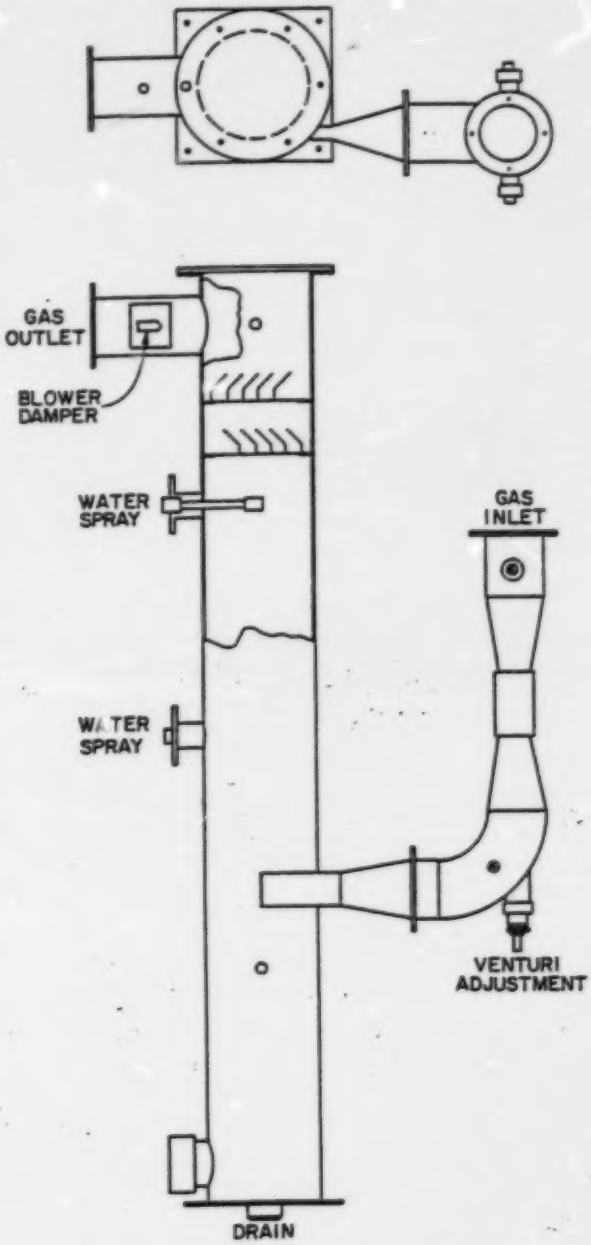


Figure 7–Venturi scrubbers.

SECTION V

PILOT PLANT OPERATION

OPERATION OF CARBON CONTACTING COLUMNS

Carbon Adsorption

During the Shirco carbon regeneration study, the unchlorinated and unfiltered secondary effluent from the Pomona Water Reclamation Plant was treated directly by the carbon adsorption system. The Pomona Water Reclamation Plant is a 0.44 cu m/sec (10 MGD) activated sludge plant, and is located adjacent to the research facility where this study was conducted. Steel piping with a diameter of 15.2 cm (6 in.) was used to transfer the unchlorinated secondary effluent from the Pomona Reclamation Plant to the Pomona Research Facility at a maximum total flow rate of 37.9 l/sec (600 gpm). A surge tank at the research site was used to hold the secondary effluent for supplying the pilot plant operation with a constant and uniform flow. The excess water from the surge tank was discharged into the sewer line, and the carbon product water was further treated by chlorination and dechlorination for the other phase of the study.

The contacting carbon columns were operated in a down-flow mode at a constant rate of 6.3 l/sec (100 gpm) thereby providing a hydraulic loading rate of 2.4 l/sec/m^2 (3.5 gpm/ft^2) and an empty-bed contact time of approximately ten minutes for each column. As indicated in Figure 2, the column feed water entered the top of the contactor through an annular distribution ring containing twenty 2.54 cm (1 in.) diameter holes around the circumference of the contactor. These annular rings were located about 2.5 m (8.3 ft) above the top of the carbon bed, and thus provided sufficient space for bed expansion during backwashing. A portion of the carbon treated water was stored in a 45 m^3 (12000 gal) storage tank and provided a sufficient amount of water for backwashing the second and third columns in the series every two and four weeks, respectively.

Backwash of the Carbon Beds

The first carbon bed was backwashed daily to maintain good hydraulic conditions for operation. The carbon columns were usually taken off stream each morning for the backwashing of the first column, which took approximately one hour to complete. The unchlorinated secondary effluent from the Pomona Water Reclamation Plant was used as wash water for the carbon bed backwash operation. The backwash sequence, as indicated in Figure 8, consisted of a surface wash at a constant rate of 1.22 l/sec/m^2 (1.8 gpm/ft^2) for 20 minutes and a stepwise backwash to a maximum rate of 7.13 l/sec/m^2 (10.5 gpm/ft^2) within a total period of approximately 35 minutes or longer until a reasonably clear backwash water was observed in the discharge line. The total

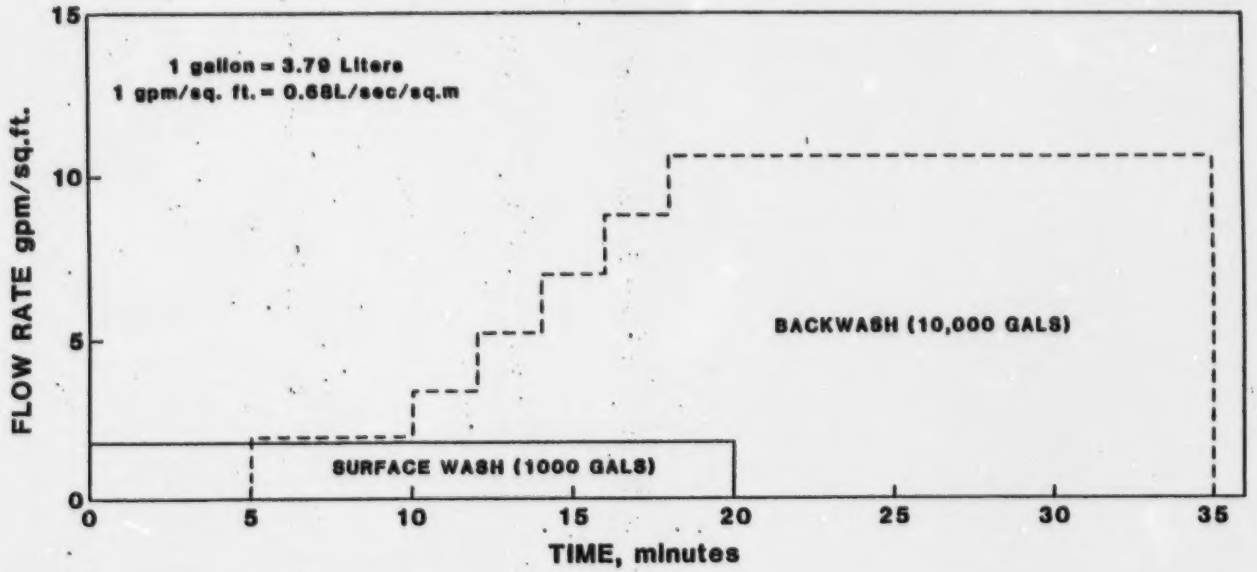


Figure 8–Carbon adsorption column backwash schedule.

volume of water used for surface wash and backwash averaged approximately 3.78 cu m (1000 gallons) and 37.8 cu m (10,000 gallons), respectively. The combined total of water consumed in the backwash process was about eight percent of the total volume of product water. During backwashing, the backwash water was discharged into a holding tank designed to catch any accidental carbon spills and to allow visual observation of the clarity of the backwash water. The backwash water, which contained some biological floc combined with carbon fines, overflowed a weir in the holding tank and was pumped into the head end of the primary sedimentation tank of the Pomona Water Reclamation Plant.

Although adequate space was provided above the carbon beds in the contacting columns for bed expansion during backwash cycle, routine carbon backwash operation was limited to a maximum upflow rate of 7.3 l/sec/m^2 (10.5 gpm/ft^2) due to the limitations on the structural strength of the underdrain screen. The measured bed expansion was about ten percent at the maximum backwash rate of 7.3 l/sec/m^2 (10.5 gpm/ft^2).

The head loss buildup through granular activated carbon columns was found to be influenced by such factors as hydraulic surface loading, carbon particle size, influent suspended solids level, and the length of filter run. The average total head loss buildup through the first carbon bed was about 0.14 kg/cm^2 (2 psig) for a 23 hour operation period during the first adsorption cycle, when the columns were operating five days a week and were shut down during week ends. During the second, third, and fourth adsorption cycles, however, the columns were operated continuously, seven days a week. In the 71 hours of continuous operation, which occurred during weekends, an average head loss build up of 0.38 kg/cm^2 (5.5 psig) occurred through the first column.

Carbon Transfer for Regeneration

The carbon contacting columns were taken off stream after they had treated a total volume of 32,200 m^3 (8.5 MG) of Pomona Water Reclamation Plant secondary effluent during the first adsorption cycle and approximately 41,600 m^3 (11.0 MG) during the three cycles which followed. The breakthrough of trace organics under study occurred during this three months of operation, and the COD removal efficiency of the carbon columns usually leveled off at this point.

The spent carbon was thoroughly backwashed before being hydraulically transferred to the elevated dewatering chamber. The backwash procedure was similar to that used for column backwash except that the last backwash step was prolonged to provide a total backwash water volume of about 71.9 m^3 (19,000 gal).

Carbon Regeneration

A 50 percent mixture of spent carbon and water was transferred from the Shirco's feed hopper by means of a screw conveyor and was deposited on top of the traveling belt inside the regeneration furnace. The traveling belt was moved by a .19 kW (1/4 HP) variable speed motor. Carbon retention time in the furnace was set at 18 to 35 minutes depending on the extent of carbon exhaustion and operating temperature of the Shirco furnace. The regeneration temperature was maintained at 760 to 815°C (1400 to 1500°F) in the first

(drying) zone and 899 to 955°C (1600 to 1750°F) in the second zone by the temperature indicator-controller. This particular temperature range was chosen since the previous regeneration furnaces tested at this site operated in a similar mode. These temperatures were also recommended by Shirco, Inc. who utilize a similar unit at their own research facilities. In general, during the first and second regeneration cycle the carbon in the final column was regenerated under lower temperatures than the carbon in the first column. The carbon in the first column, however, was regenerated under higher temperature since it was spent to a higher degree than the other two columns in the series. A controlled oxidizing atmosphere necessary for the carbon activation process was obtained by the steam generated in the drying zone and flow co-current with the carbon through the length of the furnace. The regenerated carbon was discharged from the Shirco furnace into a quench tank and was continously educted back into the contacting columns.

Initial Calibration Before Actual Operation

After initial modification, the following steps were taken to facilitate furnace operation and to calibrate individual mechanical units.

1) Water to Carbon Mixture - Spent carbon from the feed tank was fed into the furnace by a spiral stainless steel feed screw. Different ratios of water to carbon mixture were tested to determine the optimum mixture for transfer of the carbon into the furnace by this type of screw feeder. Although the feed tank was equipped with a variable speed vibrator, the carbon and water had to be mixed manually inside the tank to obtain uniform transfer of carbon with this type of inadequate feed screw.

2) Feed Rate Calibration - The feed module was equipped with a small variable speed motor which regulated the amount of carbon transferred to the regeneration furnace. The speed control dial for this motor was located on the furnace control panel with markings from one to ten. To determine the exact amount of feed carbon (grams), the dial on the control panel was set on each number for five minutes and the carbon output was measured by weighing the carbon collected at each setting. Thus, the output of wet carbon per hour could be calculated for each corresponding dial setting.

3) Retention Time Calibration - A 0.19 kW motor provided the power for the drive system of the conveyor belt. The belt speed was adjustable by a motor speed controller on the control panel. The belt was broken in by increasing the furnace temperature by 38°C (100°F) every 30 minutes until the regeneration temperature of 955°C (1750°F) was reached. The temperature was then lowered gradually to 260°C (500°F) while the belt was traveling inside the furnace. The carbon retention time was calibrated by setting the motor speed controller at a specific dial setting and then measuring the time it took for the belt to travel six inches for each of the dial settings. Knowing the length of the belt and space allowed determination of retention time.

4) Leveling Roller - This unit was designed to regulate the thickness of the carbon layer on the conveyor belt during the regeneration process. It was supposed to be adjustable according to the original design, thereby providing another control parameter in addition to carbon retention time and furnace temperature setting. However, the roller was not adjustable and it was located 3.75 cm (1.5 in.) above the conveyor belt. This distance was reduced by a Shirco engineer to 1.9 cm (0.75 in.) since this was proven by their

previous operations to be the most effective carbon layer thickness. This modification was permanent, however, and could not be altered throughout the duration of the study.

The shakedown operation lasted two weeks and resulted in the regeneration of 272 kg (600 lbs) of carbon transported from the Pomona Water Reclamation Plant.

Carbon Make-Up

Upon completion of the regeneration cycle, the carbon in each of the three contactors was thoroughly backwashed with 76 to 182 cu m (20,000 to 48,000 gal) of secondary effluent to separate and remove the carbon fines. After the carbon bed depth measurement was taken and the amount of the carbon loss was determined, the appropriate amount of make-up carbon was then added to replace the carbon lost during regeneration. The contactors were then filled with water to soak the added make-up carbon overnight. The entire contents of each contactor was then backwashed again with approximately 37.8 cu m (10,000 gal) of secondary effluent before the contactor was placed back in operation.

Sampling and Testing

Four adsorption and three regeneration cycles were conducted during the course of this study and appropriate samples were taken for evaluating the carbon adsorption and carbon reactivation efficiencies. The locations, types, and frequencies of the various samples taken during the study are described as follows:

Water Quality Monitoring

Using timer controlled solenoid valves, samples from influent and effluent of the carbon columns were collected automatically inside a refrigerator during the 23 hours of operation each day. These samples were analyzed daily for a number of parameters such as total chemical oxygen demand (TCOD) and color in order to monitor the rate of carbon exhaustion. In addition, pH and temperature determinations were performed on grab samples each morning. All analyses were performed in accordance with the Standard Methods for the Examination of Water and Wastewater.[5]

Carbon Regeneration Control Test

In the course of carbon regeneration, a number of control tests measuring such parameters as apparent density, iodine number, molasses number, and methylene blue number, were performed to regulate the regeneration process and monitor the quality of the regenerated carbon. All tests were performed using the standardized procedures of the Pittsburgh Activated Carbon Company.[6] In general, approximately 550 hours was required for each cycle resulting in the regeneration of 4,756 kg (10,500 lb) of carbon. Laboratory analysis on regenerated carbon was performed on an hourly basis for apparent density, every two hours for molasses and iodine number, and once every eight hours for methylene blue number. Grab samples of spent carbon collected during carbon transfer and the hourly samples of regenerated carbon were composited over the regeneration period. These composited carbon samples were analyzed for apparent density, iodine, methylene blue and molasses numbers, and ash content.

SECTION VI

PILOT PLANT RESULTS AND DISCUSSION

PERFORMANCE OF CARBON CONTACTING COLUMNS

Four adsorption cycles were performed with the three carbon contacting columns during the Shirco furnace regeneration study period. The average values of water quality parameters for each column during these adsorption cycles are presented in Tables 2, 3, and 4. As indicated in these tables, the average volume of secondary effluent processed through the carbon contacting columns during the four adsorption cycles was about 38,600 cu m (10.2 MG). The average pressure drop before the daily backwash of the first carbon column was approximately 0.14 kg/cm^2 (2.0 psig). The carbon columns proved to be very effective for suspended solids and turbidity removals. A major portion of the total suspended solids and turbidity removal took place in the first column in the series, accomplishing average removals of 76 percent of suspended solids and 66 percent of turbidity. The second and final columns each removed a smaller fraction of the remaining suspended solids and turbidity-causing-materials to produce a polished effluent with suspended solids as low as 0.62 mg/l and turbidity of 0.61 NTU.

Dissolved chemical oxygen demand (DCOD) and color removal by each carbon column during all four adsorption cycles are illustrated in Figures 9 through 12. Both DCOD and color were effectively removed by the carbon columns in the early portion of each adsorption cycle. However, as the carbon in the first column approached exhaustion, both DCOD and color removal seemed to level off at approximately 35 percent and 40 percent, respectively. Similarly to suspended solids and turbidity removal, much of the DCOD and color removals occurred through the first column in the series which removed an average of 50 percent of DCOD and 55 percent of color from the incoming secondary effluent during first through fourth adsorption cycles. Smaller amounts of remaining DCOD and color were removed by the second and final columns to produce effluent quality with an average level as low as 3 mg/l for DCOD and 1.7 color units during the second adsorption cycle (Table 4). This amount translates to overall DCOD and color removal of 86 and 95 percent, respectively.

The color removal after thirty minutes empty bed contact time seemed to improve slightly in the various columns after each carbon regeneration as indicated by the percentage of the removal of color units shown in Table 4. A comparison of DCOD adsorption capacities with respect to adsorption cycle is presented in Table 5. As indicated in this table, the efficiency of the DCOD removal in the first column decreased during each adsorption cycle. This demonstrates a slight loss of carbon adsorption capacity after each regeneration.

TABLE 2

Summary of the First Carbon Adsorption Column Performance

Parameter	Adsorption Cycle First	Second	Third	Fourth
Total Flow Processed, MG	8.2	10.9	10.75	11.0
Daily Pressure Drop, PSIG	1.8	2.0	2.1	2.0
Dissolved COD, mg/l				
Column Influent	29.7	21.9	26.7	27.9
Column Effluent	14.0	10.7	16.8	15.2
Color, Color unit				
Column Influent	29.7	24.3	29.2	31.6
Column Effluent	10.3	10.4	17.11	14.0
Turbidity, NTU				
Column Influent	3.5	2.54	2.7	4.8
Column Effluent	1.3	.81	1.1	1.4
Suspended Solids, mg/l				
Column Influent	6.2	5.0	5.7	8.4
Column Effluent	1.6	.89	2.0	1.6
pH				
Column Influent	7.5	7.4	7.6	7.5
Column Effluent	7.5	7.4	7.6	7.5
Temperature, °C				
Column Influent	26.7	25.2	23.45	23.2
Column Effluent	26.7	25.0	23.9	23.2
Operation Period				
On	6/ 5/79	5/ 7/80	10/ 8/80	3/17/81
Off	9/14/79	7/24/80	12/24/80	6/ 1/81

TABLE 3

Summary of the Second Carbon Adsorption Column Performance

Parameter	Adsorption Cycle First	Second	Third	Fourth
Total Flow Processed, MG	8.2	10.9	10.75	11.00
Daily Pressure Drop, PSIG	0.8	1.0	1.0	0.8
Dissolved COD, mg/l				
Column Influent	14.0	10.7	16.8	15.2
Column Effluent	6.9	5.1	7.9	9.3
Color, Color unit				
Column Influent	10.3	10.4	17.1	14.0
Column Effluent	2.8	3.6	5.4	5.4
Turbidity, NTU				
Column Influent	1.3	.81	1.1	1.4
Column Effluent	1.1	.73	.68	1.2
Suspended Solids, mg/l				
Column Influent	1.6	.89	2.0	1.6
Column Effluent	1.4	.70	.97	1.2
pH				
Column Influent	7.5	7.4	7.6	7.5
Column Effluent	7.4	7.5	7.6	7.5
Temperature, °C				
Column Influent	26.7	25.0	23.9	23.2
Column Effluent	26.6	24.9	23.4	23.2
Operation Period				
On	6/ 5/79	5/ 7/80	10/8/80	3/17/81
Off	9/14/79	7/24/80	12/24/80	6/ 1/81

TABLE 4

Summary of the Final Carbon Adsorption Column Performance

Parameter	Adsorption Cycle First	Second	Third	Fourth
Total Flow Processed, MG	8.2	10.9	10.75	11.0
Daily Pressure Drop, PSIG	0.4	0.5	0.5	0.5
Dissolved COD, mg/l				
Column Influent	6.9	5.1	7.9	9.3
Column Effluent	4.7	3.0	4.3	5.8
Color, Color unit				
Column Influent	2.8	3.6	5.4	5.4
Column Effluent	1.5	1.7	1.9	2.6
Turbidity, NTU				
Column Influent	1.1	.73	.68	1.2
Column Effluent	.99	.61	.62	.99
Suspended Solids, mg/l				
Column Influent	1.4	.70	.97	1.2
Column Effluent	1.3	.62	.88	1.0
pH				
Column Influent	7.4	7.5	7.62	7.57
Column Effluent	7.4	7.5	7.64	7.59
Temperature, °C				
Column Influent	26.6	24.9	23.4	23.2
Column Effluent	27.0	24.5	22.8	22.6
Operation Period				
On	6/ 5/79	5/ 7/80	10/ 8/80	3/17/81
Off	9/14/79	7/24/80	12/24/80	6/ 1/81

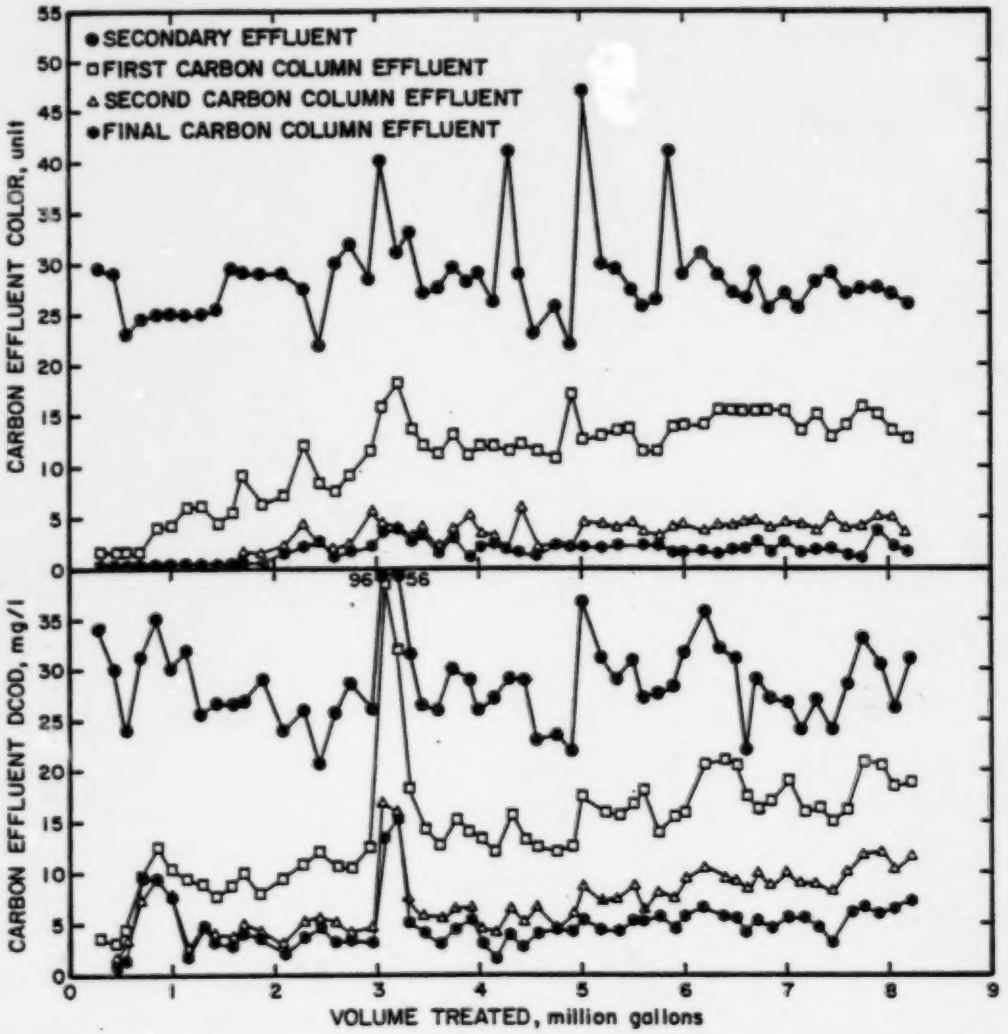


Figure 9–Dissolved COD and color removal through the carbon columns during the first adsorption cycle.

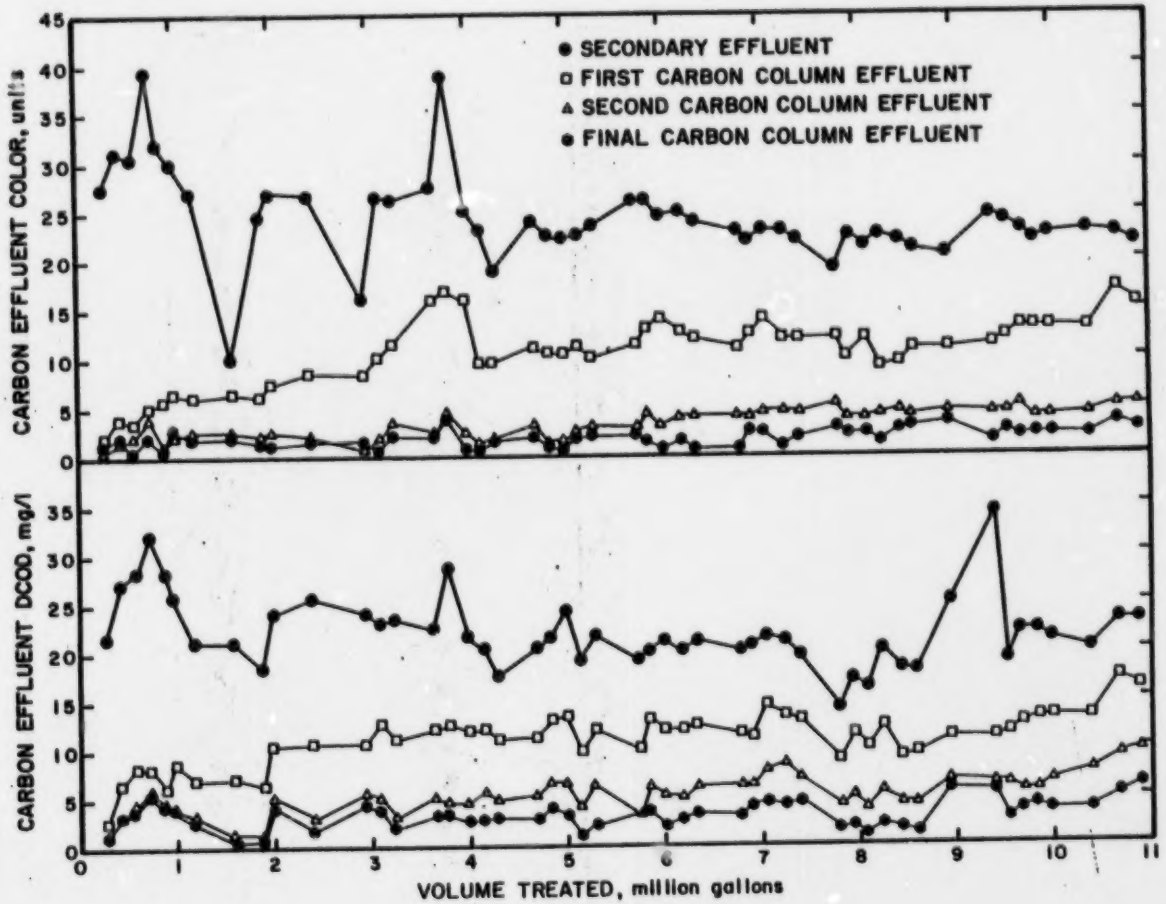


Figure 10–Dissolved COD and color removal through the carbon columns during the second adsorption cycle.

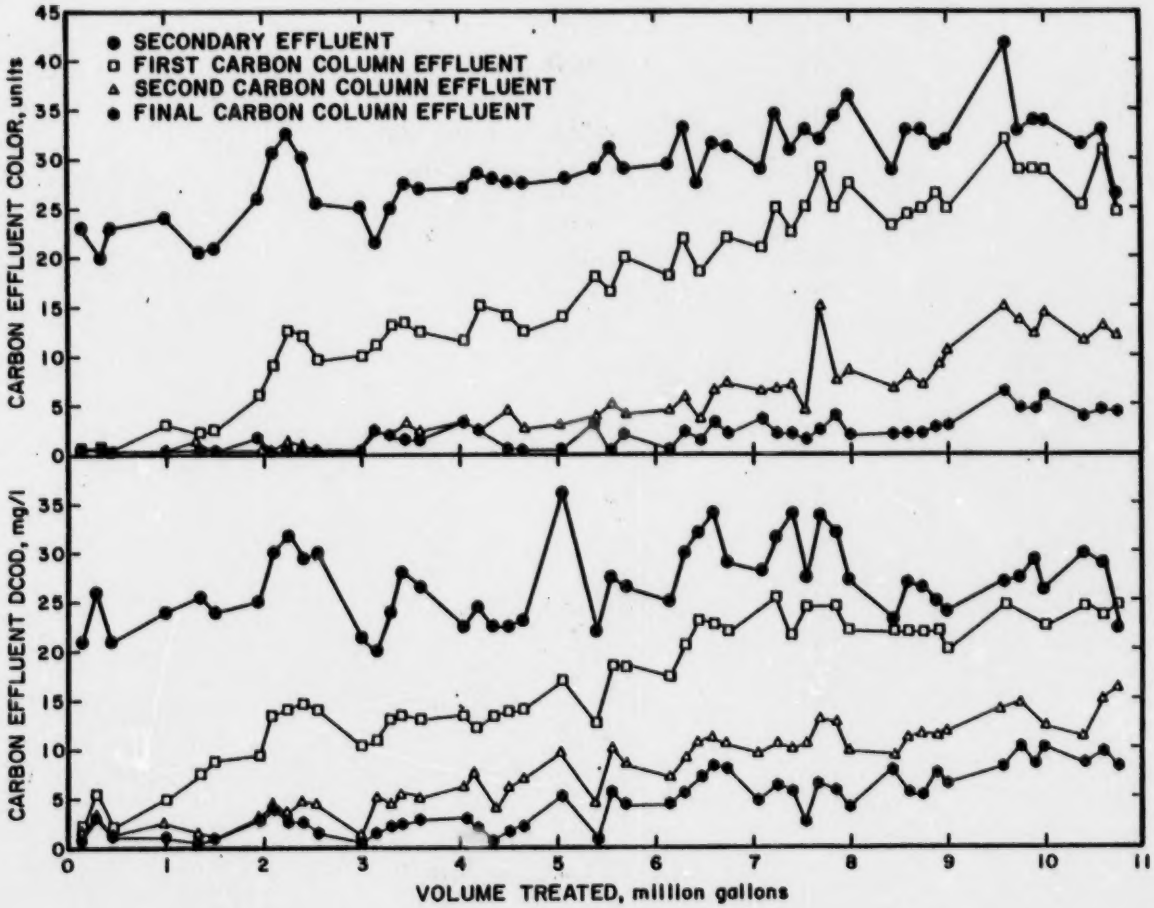


Figure 11–Dissolved COD and color removal through the carbon columns during the third adsorption cycle.

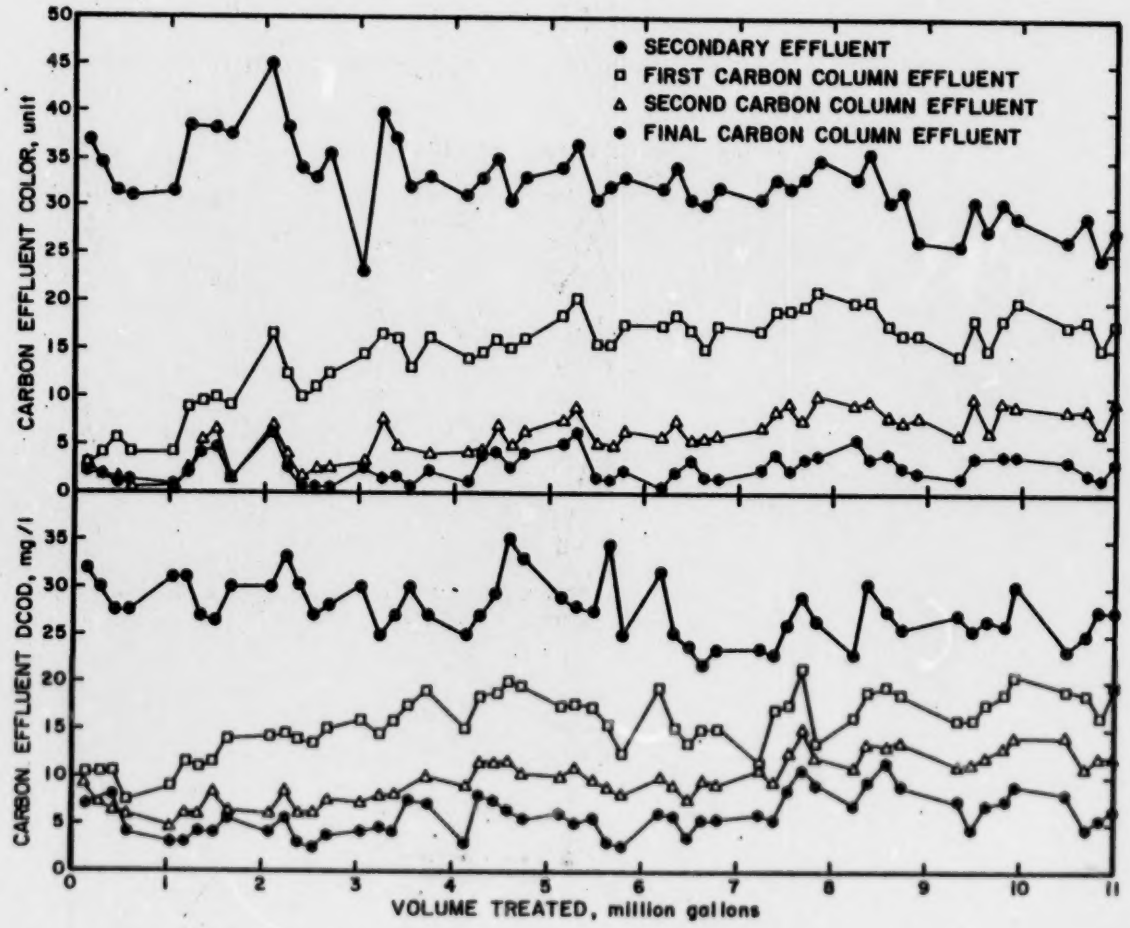


Figure 12–Dissolved COD and color removal through the carbon columns during the fourth adsorption cycle.

TABLE 5

DCOD Adsorption Capacity Comparison Among Various Adsorption Cycles

Parameter	Adsorption Cycle (first column) First	Second	Third	Fourth
Total Flow Processed	8.2	10.9	10.75	11.0
Carbon Utilized, lb	3500	3500	3500	3500
DCOD Applied, lb/lb C	0.58	0.57	0.68	0.73
DCOD Removed lb/lb C	0.31	0.29	0.25	0.33
Removal Efficiency %	53	51	37	45

Parameter	Adsorption Cycle (second column) First	Second	Third	Fourth
Total Flow Processed	8.2	10.9	10.75	11.0
Carbon Utilized, lb	3500	3500	3500	3500
DCOD Applied, lb/lb C	0.27	0.28	0.43	0.40
DCOD Removed, lb/lb C	0.14	0.13	.20	.24
Removal Efficiency %	52	46	46	60

Parameter	Adsorption Cycle (final column) First	Second	Third	Fourth
Total Flow Processed	8.2	10.9	10.75	11.00
Carbon Utilized, lb	3500	3500	3500	3500
DCOD Applied, lb/lb C	0.13	0.15	0.23	0.16
DCOD Removed, lb/lb C	0.04	.05	.09	.09
Removal Efficiency %	31	33	39	56

PERFORMANCE OF REGENERATION SYSTEM

During the initial shakedown operation of the Shirco carbon regeneration system a number of mechanical difficulties were encountered. These problems were traced to inadequate design of portions of the regeneration system. The problems were generally in the areas of the carbon feed system, leveling roller, carbon movement through the furnace (sudden stopping of the belt), faulty tracking of the belt inside the furnace, furnace and afterburner temperature control, and temperature monitoring and recording instrumentation. A number of system modifications were performed, and most of the problems were corrected before the first carbon regeneration cycle. Some problems, however, were major design problems which could not be corrected at the research site.

The shakedown operation lasted two weeks and resulted in the regeneration of 272 kg (600 lbs) of carbon transported from the Pomona Water Reclamation Plant.

Furnace Operating Temperature

Seventeen hours of operation was broken down into two shifts each day during the entire course of the study. This schedule provided 14 hours of continous carbon regeneration each day as the Shirco furnace required approximately one hour to warm up during start-up operation in the morning and two hours to cool down during shut-down operation in the evening. The actual feeding of the spent carbon into the furnace during the last minutes of the warm up period seemed to rapidly increase the inside temperature of the furnace to the desired level.

The daily average operating temperature during each of the three regeneration cycles for individual carbon columns A, B, and C (first, second and third columns in series) are shown in Tables 6 through 14. The data are presented in this fashion since it clearly indicates the day-to-day furnace operating temperature and its direct effect on the possibility of restoring the spent carbon to the optimum capacity for its next adsorption cycle. A summary of these average daily operating temperatures in addition to the average operating temperature at various locations along the length of the entire regeneration system is presented in Table 15. As is apparent from Tables 6, 7, and 8 during the first carbon regeneration cycle, the furnace operating temperature generally ranged from 760 to 815°C (1400 to 1500°F) for Zone A (drying zone) and from 899 to 955°C (1650 to 1750°F) for Zone B (regeneration zone). Because the first carbon column in the series (column A) removed most of the DCOD and turbidity loading from the secondary effluent during each adsorption cycle, it was regenerated under a higher temperature of 955°C (1750°F). The second and third carbon columns in the series (columns B and C), however, were much less exhausted and, therefore, required a lower regeneration temperature of 927°C (1700°F) and 899°C (1650°F), respectively, to achieve the same restoration quality.

As indicated in Table 8, during the last several days of regeneration in the first cycle, three of the heating elements in the regeneration zone broke down gradually and became nonfunctional after approximately 550 hours of operation. This caused a considerable temperature drop in the furnace. However, the small amount of the spent carbon remaining in the drain bin was regenerated under this condition and returned to column C to facilitate the

TABLE 6

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column A During the First Regeneration Cycle

Date	Temperature Maintained F°		Residence Time Minutes	Energy Consumption		Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
	Zone A	Zone B		Total kWh	kWh/lb Regenerated Carbon				
First Regeneration Cycle	Spent Carbon								
3/ 3/80	1400	1700	26	*200	--	0.606	518	176	176
3/ 5/80	1400	1750	26	*290	--	0.516	912	210	269
3/ 6/80	1400	1750	22	510	--	0.515	916	231	276
3/ 7/80	1400	1750	22	530	--	0.525	859	226	265
3/10/80	1400	1750	22	530	--	0.523	868	235	265
3/11/80	1500	1770	22	520	--	0.520	859	231	275
3/12/80	1500	1750	22	*440	--	0.516	856	228	275
3/13/80	1400	1750	22	570	--	0.537	832	232	232
3/14/80	1450	1760	22	510	--	0.536	855	223	267
3/17/80	1450	1760	22	540	--	0.520	872	253	274
3/18/80	1450	1750	22	540	--	0.514	863	247	264
3/19/80	1450	1750	22	530	--	0.520	869	228	269
3/20/80	1450	1750	22	510	--	0.521	830	241	266
3/21/80	1450	1625	22	*210	--	0.505	885	259	263
						0.507	End of Regeneration		

* Less than 14 hours of routine operation

TABLE 7

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column B During the First Regeneration Cycle

Date	Temperature Maintained F°		Residence Time Minutes	Energy Consumption		Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
	Zone A	Zone B		Total kWh	kWh/lb Regenerated Carbon				
First Regeneration Cycle	Spent Carbon								
3/25/80	1400	1700	22	680	--	0.558	627	198	261
3/26/80	1400	1710	22	570	--	0.500	898	248	265
3/27/80	1400	1700	22	550	--	0.501	925	236	263
3/28/80	1400	1700	22	450	--	0.502	914	245	265
3/31/80	1400	1700	22	460	--	0.517	963	232	262
4/ 1/80	1400	1720	22	550	--	0.512	881	228	265
4/ 2/80	1400	1770	22	550	--	0.521	897	210	264
4/ 3/80	1400	1750	22	560	--	0.519	911	236	262
4/ 4/80	1400	1740	22	540	--	0.522	905	241	260
4/ 7/80	1400	1740	22	560	--	0.518	821	246	267
4/ 8/80	1400	1740	22	*380	--	0.511	931	234	271
						0.505	909	247	277

* Less than 14 hours of routine operation

TABLE 8

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column C During the First Regeneration Cycle

Date	Temperature Maintained F° Zone A	Zone B	Residence Time Minutes	Energy Consumption Total kWh	kWh/lb Regenerated Carbon	Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
First Regeneration Cycle	Spent Carbon					0.547	774	229	276
4/10/80	1400	1660	22	530	--	0.508	889	240	265
4/11/80	1400	1710	18	630	--	0.510	904	228	272
4/14/80	1400	1700	16	630	--	0.504	909	240	270
4/15/80	1400	1660	16	560	--	0.508	902	232	265
4/16/80	1400	1650	16	590	--	0.501	933	240	275
4/17/80	1400	1650	16	580	--	0.502	924	258	276
4/18/80	1400	1660	16	*320	--	0.515	902	234	274
4/21/80	1400	1650	16	*270	--	0.505	868	247	269
4/22/80	1400	1650	16	*270	--	0.500	895	249	-
4/24/80	1400	1420	16	**230	--	0.505	970	256	280
4/25/80	1380	1330	16	**270	--	0.514	911	217	265
4/28/80	1380	1320	16	**410	--	0.516	912	210	268

* Less than 14 hours of routine operation
** Deterioration and breakdown of the heating elements

TABLE 9

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column A During the Second Regeneration Cycle

Date	Temperature Maintained F° Zone A	Zone B	Residence Time Minutes	Energy Consumption Total kWh	kWh/lb Regenerated Carbon	Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
2nd Regeneration Cycle	Spent Carbon					0.569	633	189	243
8/ 5/80	1400	1630	22	430	--	0.537	743	230	255
8/ 6/80	1400	1665	22	440	--	0.535	752	237	254
8/ 7/80	1400	1650	22	430	--	0.541	732	238	255
8/ 8/80	1400	1695	22	*380	--	0.546	725	224	255
8/11/80	1400	1675	22	490	--	0.541	752	232	256
8/12/80	1400	1745	22	420	--	0.525	807	251	256
8/13/80	1400	1700	22	480	--	0.543	789	237	257
8/14/80	1450	1745	22	450	--	0.532	776	240	257
8/15/80	1425	1740	22	440	--	0.530	775	239	256
8/18/80	1400	1720	22	430	--	0.532	779	232	255
8/19/80	1400	1710	22	*220	--	0.534	775	236	258
8/20/80	1400	1740	22	*180	--	0.527	786	265	253
8/21/80	1400	1680	22	440	--	0.534	791	235	240
8/22/80	1440	1700	22	450	--	0.530	801	244	250
8/25/80	1460	1590	22	*240	--	0.548	747	232	252

* Less than 14 hours of routine operation

TABLE 10

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column B During the Second Regeneration Cycle

Date	Temperature Maintained F° Zone A	Zone B	Residence Time Minutes	Energy Consumption Total kWh	kWh/lb Regenerated Carbon	Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
2nd Regeneration Cycle	Spent Carbon					0.565	700	206	250
8/27/80	1400	*1655	18	460	1.40	0.527	822	230	255
8/28/80	1400	*1685	18	500	1.18	0.535	818	222	255
8/29/80	1400	*1670	16	520	1.22	0.538	802	220	260
9/ 2/80	1400	*1665	16	490	1.24	0.537	837	223	257
9/ 3/80	1400	*1665	18	560	1.24	0.535	816	230	257
9/ 4/80	1400	*1675	18	600	1.34	0.536	838	226	261
9/ 5/80	1400	*1685	18	560	1.39	0.531	834	238	255
9/ 8/80	1400	1700	18	550	1.56	0.525	834	254	258
9/ 9/80	1400	1700	22	510	1.59	0.523	856	259	261
9/10/80	1400	1720	18	560	1.51	0.530	834	253	261

* Maximum attainable temperature

TABLE 11

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column C During the Second Regeneration Cycle

Date	Temperature Maintained F° Zone A	Zone B	Residence Time Minutes	Energy Consumption Total kWh	kWh/lb Regenerated Carbon	Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
2nd Regeneration Cycle	Spent Carbon					0.535	810	217	255
9/15/80	1400	1700	18	560	1.58	0.520	860	235	266
9/16/80	1400	1670	22	560	1.44	0.521	846	225	260
9/17/80	1310	1595	26	460	1.46	0.522	852	231	263
9/18/80	1400	1700	18	*470	1.50	0.517	870	233	265
9/19/80	1400	1700	18	570	1.45	0.519	883	241	265
9/22/80	1400	1645	18	*250	1.74	0.522	853	233	-
9/23/80	1400	1670	22	540	1.57	0.518	857	246	269
9/24/80	1400	1650	16	570	1.40	0.524	865	256	267
9/25/80	1360	1640	18	520	1.60	0.519	875	252	265
9/26/80	1390	1640	18	500	1.56	0.514	873	240	271
9/29/80	1365	1565	18	*210	1.68	0.516	871	227	-
9/30/80	1380	1600	16	120	2.11	End of Regeneration			

* Less than 14 hours of routine operation

TABLE 12

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column A During the Third Regeneration Cycle

Date	Temperature Maintained F° Zone A	Zone B	Residence Time Minutes	Energy Consumption Total kWh	kWh/lb Regenerated Carbon	Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
3rd Regeneration Cycle	Spent Carbon					0.553	623	211	247
1/ 5/81	1395	1695	22	*180	--	0.582	697	224	247
1/ 6/81	1400	1675	22	*210	1.79	0.566	711	234	248
1/ 7/81	1410	1690	22	*240	1.73	0.546	736	236	247
1/ 8/81	1410	1710	22	550	1.75	0.546	730	236	252
1/ 9/81	1335	1540	22	510	1.48	0.558	706	220	254
1/12/81	1400	1700	22	540	1.49	0.549	745	246	248
1/13/81	1400	1650	22	530	1.65	0.549	726	238	252
1/15/81	1500	1700	22	550	1.63	0.533	778	246	253
1/16/81	1500	1700	22	550	1.57	0.536	780	252	245
1/19/81	1500	1700	26	500	1.88	0.523	783	268	255
1/20/81	1500	1750	18	560	1.57	0.530	764	252	250
1/21/81	1500	1650	26	470	1.68	0.532	769	241	-
1/22/81	1500	1650	35	440	2.47	0.497	817	305	266
1/23/81	1500	1750	22	520	1.84	0.503	812	300	265

* Less than 14 hours of routine operation

TABLE 13

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column B During the Third Regeneration Cycle

Date	Temperature Maintained F°		Residence Time Minutes	Energy Consumption		Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
	Zone A	Zone B		Total kWh	kWh/lb Regenerated Carbon				
3rd Regeneration Cycle	Spent Carbon					0.567	640	207	249
1/27/81	1500	1650	18	580	1.47	0.545	746	228	250
1/28/81	1500	1650	22	530	1.54	0.540	761	249	262
1/29/81	1500	1650	26	490	1.65	0.537	759	251	253
1/30/81	1500	1650	35	440	2.12	0.527	760	274	256
2/ 2/81	*1473	1700	18	610	1.43	0.547	768	243	254
2/ 3/81	*1487	1700	22	540	1.49	0.541	756	247	253
2/ 4/81	1500	1700	26	500	1.66	0.529	783	264	264
2/ 5/81	1500	1700	35	450	1.93	0.520	772	280	262
2/ 6/81	1500	1750	18	**540	1.35	0.539	761	245	252
2/ 9/81	1500	1750	22	540	1.56	0.529	757	263	262
2/10/81	1500	1750	26	470	1.69	0.521	790	270	259
2/11/81	1500	1750	18	520	1.47	0.539	755	248	261

* Unable to maintain 1500°F

** 13 hours of operation instead of 14

TABLE 14

Temperature Profile and Results of Laboratory Analyses on Regenerated Carbon

From Column C During the Third Regeneration Cycle

Date	Temperature Maintained F° Zone A	Zone B	Residence Time Minutes	Energy Consumption Total kWh	kWh/lb Regenerated Carbon	Average Apparent Density	Average Iodine #	Average Molasses #	Average Methylene Blue #
3rd Regeneration Cycle	Spent Carbon					0.527	801	224	273
2/18/81	1500	1650	18	540	1.31	0.520	823	229	268
2/19/81	1500	1650	22	490	1.47	0.523	853	233	270
2/20/81	1500	1650	26	460	1.60	0.517	863	252	271
2/23/81	1500	1700	18	530	1.43	0.520	857	247	272
2/24/81	1500	1700	22	*480	1.67	0.511	875	263	273
2/25/81	1500	1700	26	470	1.80	0.502	866	242	277
2/26/81	1500	1750	18	**420	1.72	0.513	868	251	279
2/27/81	1500	1750	18	550	1.62	0.516	870	264	278
3/ 2/81	1500	1750	22	540	1.83	0.504	854	275	268
3/ 3/81	1500	1750	26	480	1.97	0.495	860	286	279
3/ 4/81	1500	1700	22	*460	1.68	0.505	871	273	278
3/ 5/81	1500	1700	22	**520	1.74	0.507	849	275	279
3/ 6/81	1500	1700	22	**240	2.00	0.506	810	248	-

* 13 hours of operation instead of 14
** 5 to 10 hours of operation instead of 14

TABLE 15

Summary of Shirco Regeneration System Operating Temperatures (F°)

Thermocouple Number	Location	Regeneration Cycle								
		First Cycle			Second Cycle			Third Cycle		
		Column			Column			Column		
		A	B	C	A	B	C	A	B	C
One	Zone A (drying zone)	1425	1400	1400	1400	1400	1375	1450	1500	1500
Two	Zone B (regeneration zone)	1750	1720	1650	1700	1675	1650	1700*	1700*	1700*
Three	Furnace exhaust	1740	1700	1645	1700	1650	1650	1700	1675	1675
Four	Afterburner inlet	1150	1140	1100	1100	1075	1075	1175	1150	1125
Five	Afterburner	1400	1400	1400	1400	1400	1400	1400	1400	1400
Six	Afterburner exhaust	1150	1100	1100	1150	1125	1125	1175	1175	1150
Seven	Exhaust to atmosphere	100	90	90	95	90	90	85	90	80

NOTE: * During the third regeneration cycle the regeneration temperature was set at 1650, 1700, and 1750°F. Therefore, the 1700° temperature reported in this column is the overall average temperature.

start of the second adsorption cycle. Before the second regeneration cycle began the broken heating elements were replaced and the regeneration temperature criteria were the same as during the previous regeneration.

As is apparent from Table 10, during the second regeneration cycle the desired temperature of 927 to 955°C (1700 to 1750°F) could not be achieved due to a constant breakage of deteriorated heating elements. Finding an optimum temperature in relation to minimum energy usage and maximum restoration of carbon quality became very difficult during this second regeneration cycle, as the entire stock of the spare heating elements was gradually used up. A number of other technical problems such as periodic failure of the carbon feed system and drastic mistraction of the conveyor belt to one side of the furnace were also encountered during this period.

In an effort to make the third and final regeneration the most productive cycle in the evaluation of the Shirco furnace, a complete matched set of heating elements for the furnace and afterburner was installed to replace the entire older heating elements in these two units. Thus, as indicated in Tables 13 and 14, each of the carbon columns was regenerated under three sets of temperature, 899, 927, and 955°C (1650, 1700, and 1750°F). The drying zone was set at 815°C (1500°F). In general, the best temperature for regeneration of this type of carbon with the Shirco furnace was found to be 955°C (1750°F) with the drying zone temperature at 815°C (1500°F). Although this value varied depending on quality and quantity of the adsorbed material in the carbon pores and retention time in the regeneration furnace, in general, a higher regeneration temperature at a low retention time proved to be more efficient and cost-effective than achieving the same regeneration quality under low temperature and high retention time.

Carbon Feed Rate and Retention Time

In the Shirco furnace the feed rate is directly dependent on the desired carbon retention time in the furnace which in turn is controlled by the traveling speed of the conveyor belt inside the furnace. Maximum throughput for the feed rate was maintained so that the carbon layer would cover the width of the conveyor belt for any given retention time. As indicated in Table 13, during the third regeneration cycle the retention time was set at 18, 22, 26, and 35 minutes. The feed rate was maintained at its maximum for each retention time, and carbon thickness was at a constant 1.9 cm (3/4 in.). The maximum output of the furnace was about 14 kg/hr (31 lb/hr) at 18 minutes retention time, and the minimum output was 7.3 kg/hr (16 lb/hr) at 35 minutes retention time. Thirty-five minutes retention time was found to be much too long since it not only caused partial burning and enlargement of the carbon pores at 927°C (1700°F) or higher but it also reduced the carbon throughput rate to an uneconomical level. Partial burning of the carbon was apparent from a blue flame which could be seen from the furnace's view port during regeneration at high temperatures and long retention time (35 minutes). Iodine and molasses numbers are related to the surface area of the pores with a diameter larger than 10 and 28 angstroms, respectively. Therefore, a slight reduction of iodine number and the increase of molasses number at 35 minutes retention time and at temperatures higher than 927°C (1700°F) is thought to be indicative of carbon pore enlargement. Eighteen minutes retention time was found to be very efficient for regeneration of the lightly loaded carbon, i.e., that in the third carbon column which had removed only an average of 0.09 kg of DCOD per kg of carbon. The Shirco furnace

was generally operated at 22 minutes retention time which resulted in an average output of 9.1 to 11.3 kg (20 to 25 lb) per hour. Tables 13 and 14, and Figures 13 and 14 clearly demonstrate the correlation between various retention periods and furnace temperature settings in relation to the extent of restoration of regenerated carbon as measured by various chemical analyses.

As is shown in these figures, 26 minutes retention time at 955°C (1750°F) was very effective in restoration of spent carbon. The 22 minutes retention time was, however, more economical in power consumption per pound of carbon regenerated. These figures also indicate that iodine number was not improved drastically by higher temperatures and longer retention times. The molasses number and apparent density which are also indicative of change in adsorption parameters were improved considerably at 26 minutes retention time and 955°C (1750°F).

Power Consumption and Carbon Loss

Table 16 summarizes the Shirco furnace energy consumption and carbon loss during the course of the regeneration study. The total power consumption for carbon regeneration by the Shirco furnace was 17570, 16550, and 18740 KWH for the first, second, and third regeneration cycles, respectively. Power consumption for the entire regeneration unit was measured by a watthour meter, and was recorded daily at the start up and shut down of the furnace. The daily power consumption in the process of carbon regeneration for each individual carbon column during all three cycles is also presented in Tables 6 through 14. The average of the total carbon losses in the subsequent three regeneration cycles was 9.0, 7.7, and 6 percent. The low value of 6 percent carbon loss which occurred during the final regeneration cycle is indicative of the value which can be obtained repeatedly when other problems such as the breaking of heating elements or mistraction of the conveyor belt do not occur. Values as low as 3 and 5 percent carbon loss from regeneration of the second and final carbon column were obtained following the replacement of all the heating elements in the furnace and the development of a device which kept the conveyor belt from mistracking to one side. The carbon in columns B and C was much cleaner than the first column in the series. Therefore, it was regenerated under lower furnace temperature settings and shorter retention times. This could partly explain the lower carbon loss and energy consumption during all three regeneration cycles for columns B and C in comparison to column A.

Carbon Adsorption Capacity

In the course of thermal regeneration, the organic pollutants on the surfaces of the external and pore areas of carbon are oxidized and removed. This oxidation process, however, does not completely remove the adsorbed organics from the carbon pores. Therefore, a certain amount of the capacity is normally lost in every thermal regeneration cycle. In addition, the change of pore size distribution during the regeneration process may also contribute to the reduction of carbon adsorption capacity. The carbon adsorption capacity recovery was monitored by the determination of the iodine number, molasses number, and methylene blue number on both spent and regenerated carbons. Tables 17, 18, and 19 summarize the values of these adsorption parameters obtained during the Shirco furnace regeneration study. The results

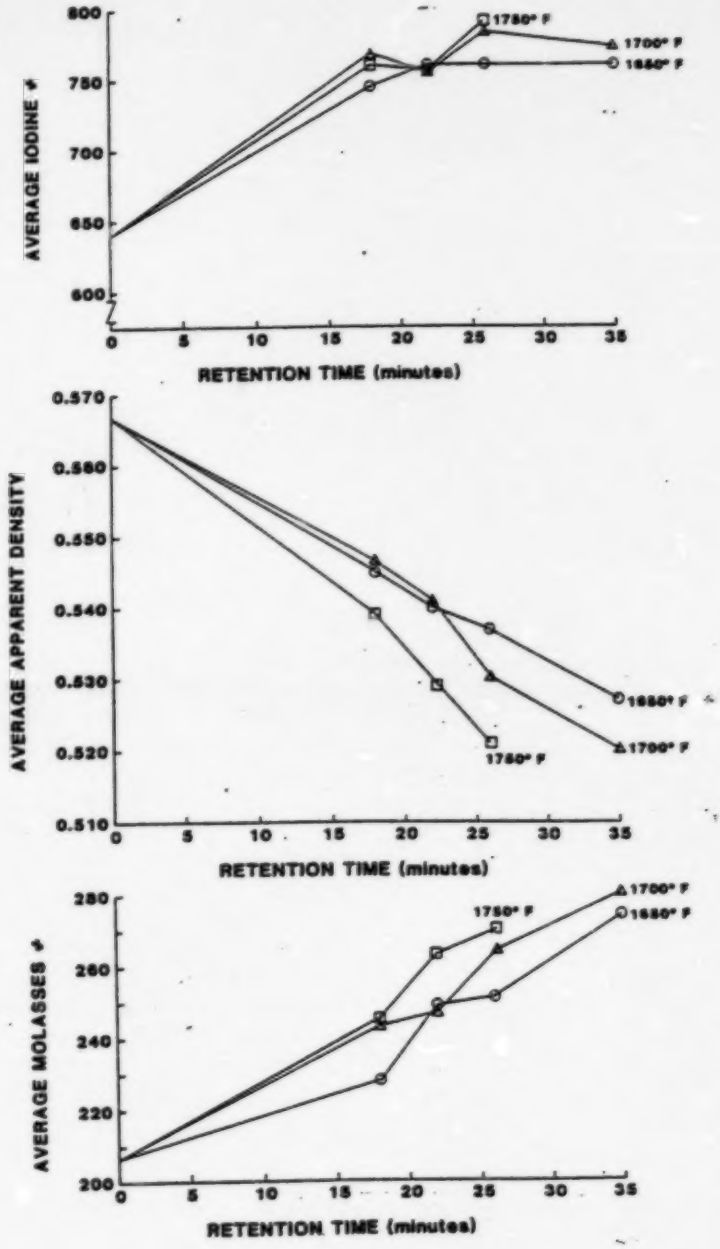


Figure 13–Effect of retention time and temperature on regeneration of the carbon in Column B.

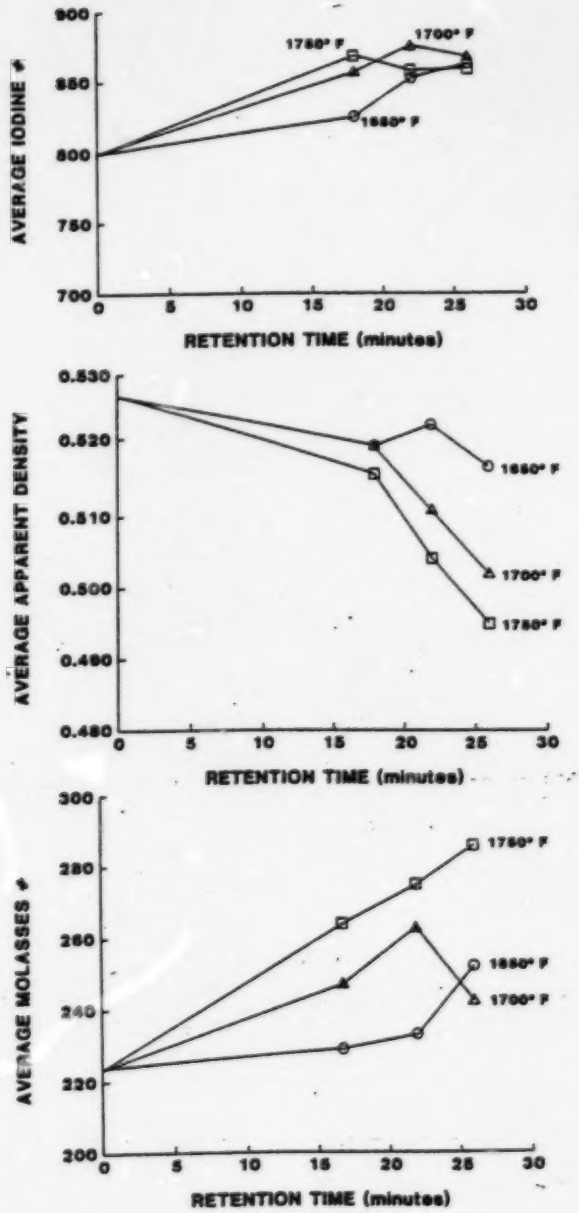


Figure 14–Effect of retention time and temperature on regeneration of the carbon in Column C.

TABLE 16

Shirco Furnace Energy Consumption and Carbon Loss

Carbon Column	Carbon Loss			Energy Consumption
	Sampling and Transfer	Regeneration Furnace	Total Loss	KWH
1st Regeneration cycle				
A	3%	*14%	17%	6430
B	2%	6.5%	8.5%	5850
C	2%	6.5%	8.5%	5290
Average loss and total energy	2.3%	9%	11.3%	17570
2nd Regeneration Cycle				
A	3%	*12%	15%	5910
B	2%	6%	8%	5310
C	2%	5%	7%	5330
Average loss and total energy	2.3%	7.7%	10%	16550
3rd Regeneration Cycle				
A	1%	10%	11%	6350
B	1%	3%	4%	6210
C	1%	5%	6%	6180
Average loss and total energy	1%	6%	7%	18740

*Problem with carbon feed system

of the daily laboratory analyses on regenerated carbon for determination of iodine, molasses, and methylene blue numbers are also presented in Tables 6 through 14. As indicated in Table 1, the iodine numbers of the virgin Calgon Filtrasorb 300 granular activated carbon were about 1079, 1071 & 1073 mg/g for columns A, B, and C, respectively. By the end of the first adsorption cycle these values were reduced to 518, 627, and 774 mg/g which was equivalent to a 54, 41, and 28 percent reduction in iodine number for the first, second, and final columns, respectively. The reduction in iodine number was partially recovered from 518, 627, and 774 mg/g to 937, 914, and 910 mg/g for columns A, B, and C, respectively after the first regeneration by the Shirco furnace. A continuing decrease in the iodine number with respect to regeneration cycle is apparent from Tables 17, 18, and 19, although the cyclic thermal regeneration was basically effective in restoring the operational adsorption capacity.

The molasses number was found to gradually increase with each successive regeneration cycle. Since the molasses number is related to the surface area of the pores with a diameter larger than 28 angstroms, the increase in molasses number indicated an enlargement of micropore structures to macropore structures in the carbon during the repeated thermal regeneration process. This shift in pore size distribution also caused a reduction of total surface area of the carbon, which was indicated by the reduction of the iodine number. The molasses number of the virgin carbon was about 233, 226, and 238 for columns A, B, and C, respectively. At the end of the third regeneration cycle the molasses numbers had increased to 261, 255, and 257, and increase of 12, 13, and 8 percent for the first, second and final columns, respectively. The third carbon column contained cleaner carbon than the other two columns in the series and, hence, was subjected to lower temperature and retention times during the regeneration cycles and had the lowest iodine number decrease and molasses number increase after three thermal regeneration cycles (See Table 19). The increase in molasses number seemed to improve the color removal capability of carbon slightly, as shown in Figures 9 through 12.

Methylene blue number determination was another parameter used to measure pore enlargement during the regeneration cycles. This number is related to surface area of carbon pores with diameters larger than 15 angstroms. As is apparent from Tables 17, 18, and 19, the methylene blue number of the carbon was not affected to the same extent as iodine and molasses number during the thermal regeneration.

The ash content of the regenerated carbon, which measured the buildup of inorganic residues, increased from a level of 6.2, 6.7 and 6.7 for the virgin carbon to 9.0, 8.7, and 7.8 percent for carbon in columns A, B, and C, respectively, after three regeneration cycles. Similarly, the apparent density of the regenerated carbon fluctuated from 0.525, 0.532, and 0.524 to 0.542, 0.534, and 0.511 g/cm^3 for carbon columns A, B, and C, respectively, as shown in Tables 17 through 19.

The effects of the Shirco furnace carbon regeneration on the various carbon characteristic numbers as discussed above are similar to those reported for the multiple hearth study.[1] Apparently, all three regeneration systems the multiple hearth, rotary kiln, and Shirco furnace could repeatedly restore the carbon adsorption capacity equally well following each adsorption cycle.

TABLE 17

Results of The First Column, Carbon Quality Control Tests

Parameter	First Regeneration		Second Regeneration		Third Regeneration	
	S	R	S	R	S	R
AD, g/cc	0.606	0.520	0.569	0.536	0.574	0.542
IN mg/g	518	937	636	769	623	747
MN	176	236	189	238	211	261
MBN, mg/g	176	269	243	254	247	252
Ash, %	8.6	--	8.8	9.1	8.3	9.0

NOTES: S = Spent Carbon
AD = Apparent density
MN = Molasses number
R = Regenerated Carbon
IN = Iodine Number
MBN = Methylene blue number

TABLE 18

Results of The Second Column, Carbon Quality Control Tests

Parameter	First Regeneration		Second Regeneration		Third Regeneration	
	S	R	S	R	S	R
AD, g/cc	0.558	0.512	0.565	0.532	0.567	0.534
IN mg/g	627	914	700	829	640	764
MN	198	237	206	235	207	255
MBN, mg/g	261	266	250	258	249	257
Ash, %	8.3	--	7.9	8.3	7.7	8.7

NOTES: S = Spent Carbon
R = Regenerated Carbon
AD = Apparent density
IN = Iodine Number
MN = Molasses number
MBN = Methylene blue number

TABLE 19

Results of The Third Column, Carbon Quality Control Tests

Parameter	First Regeneration		Second Regeneration		Third Regeneration	
	S	R	S	R	S	R
AD, g/cc	0.547	0.507	0.535	0.519	0.527	0.511
IN mg/g	774	910	810	864	801	855
MN	229	238	217	238	224	257
MBN, mg/g	276	271	255	266	273	274
Ash, %	8.7	--	7.6	8.1	7.1	7.8

NOTES: S = Spent Carbon
R = Regenerated Carbon
AD = Apparent density
IN = Iodine Number
MN = Molasses number
MBN = Methylene blue number

Furnace Components Life Expectancy

The major components used in the Shirco furnace system are the heating elements, high-temperature conveyor belt, and ceramic fiber blanket insulation system, which were claimed by the manufacturers to have a nominal life expectancy of 3, 5, and 5 years, respectively. After approximately 1,800 hours of operation during the eighteen months of the study, the following observations could be made concerning the life expectancy of Shirco furnace components. These are based on inspection of the furnace at the end of final regeneration. The ceramic fiber blanket which insulated the furnace and the afterburner appeared to be intact at all points, and no signs of deterioration were detected. The conveyor belt was inspected before and after each regeneration cycle. By the end of the first regeneration cycle (approximately 550 hours) one side of the conveyor belt was stretched causing the belt to be longer on one side. Further stretching of the conveyor belt during the second regeneration cycle caused it to mistrack periodically to one side of the furnace. Due to further stretching and corrosive damage during final regeneration, the conveyor belt required replacement after approximately 1800 hours of operation. As mentioned before, some of the heating elements had to be replaced after 550 hours of operation. The entire 24 units of the heating elements in the furnace were replaced before the final regeneration. Since several of the new heating elements broke in half and became inoperative by the last days of final regeneration after operating for approximately 600 hours, the average life of this component is estimated to be no longer than 750 hours.

PERFORMANCE OF AIR POLLUTION CONTROL SYSTEM

The Shirco furnace was equipped with an air pollution control system consisting of an afterburner and venturi wet scrubber. A temperature of 760°C (1400°F) was maintained by a set of 12 heating elements inside the afterburner, and two small fans provided the combustion air for further oxidation of the furnace off gases. A source test for the determination of emissions from the Shirco furnace and its afterburner was scheduled during the first regeneration cycle. However, due to the breakdown of several heating elements in the furnace and the resulting temperature drop in the regeneration system, the testing had to be postponed and was rescheduled during the third regeneration cycle.

The flue gases at the afterburner inlet and the scrubber outlet (stack) were tested by Truesdail Laboratories of Los Angeles, California for flow rate, particulate matter, sulfur oxides (SO_x), nitrogen oxides (NO_x), moisture (water vapor), major gas components (CO_2, CO, and O_2), and volatile hydrocarbons. In addition, the tests for NO_x, volatile hydrocarbons, and major gas components were conducted on flue gases at the outlet of the afterburner just ahead of the venturi scrubber. The flue gas flow rate was determined using a pitot tube velocity traverse method. A special pitot tube and magnetic draft gauge were utilized for the measurement. The gas temperature was measured with a chromelalumel thermocouple and a portable potentiometer. Particulate matter and sulfur oxides were collected by the same sampling train. A stainless steel probe was placed to extract the sample from the flue and was followed by a heated glass fiber filter. This filter was then followed by an impinger train filled with

200 ml of 3 percent hydrogen peroxide solution, and was connected to a vacuum pump and a gas meter. The collection in the probe and on the filter represented the particulate matter and was determined by weighing after drying at 100°C. The water extract of this collection was analyzed for free sulfuric acid and total sulfate. The impinger's collection was also extracted with chloroform to determine condensable hydrocarbons.

The nitrogen oxides were determined by the phenoldisulfonic acid method on the grab samples collected simultaneously at all three sample points at equal time intervals during the particulate matter sampling. The water vapor was calculated from the volume of condensate collected in the particulate matter sampling train impingers.

The major gas components (CO_2 , O_2, and CO) were determined on the gas phase of the NO_x grab samples; CO_2 and O_2 were determined by an orsat analysis, and CO determination was made by gas chromatography. The volatile hydrocarbons samples were collected in duplicate at all three locations simultaneously. A stainless steel trap immersed in a dry ice bath followed by an evacuated 8.2 liter tank was used to collect the samples. The results of these tests are presented in Table 20. The measured emissions were well below the emission limit allowed by South Coast Air Quality Management District (SCAQMD), which is indicative of the adequacy of this type of air pollution control system.

COST ESTIMATES

Criteria for Cost Estimates:

The furnace capacity used for cost comparison analysis is 183 kg/hr (400 lb/hr). This capacity is based on the requirement of a typical 0.44 m^3/sec (10 MGD) carbon adsorption plant with a carbon exhaustion rate of 75 g/m^3 (650 lb/MG). Table 21 shows a summary of the various assumptions used for the preparation of the cost estimates.

The cost estimates for the Shirco furnace system have been divided into two subcategories; namely, capital cost and operation and maintenance costs. The equipment cost consists of the carbon feed system, furnace system, and the air pollution control system which consisted of an afterburner and venturi wet scrubber. The capital cost also includes the initial engineering cost, equipment shipping and installation cost, and contingency. The operation and maintenance costs include the utilities, operation and maintenance labor, carbon make-up, and maintenance materials consisting of heating elements and conveyor belt replacement.

Itemized Cost Estimates:

A summary of the various cost items in shown in Tables 22 and 23. Table 22 cost estimates are based on values which were obtained directly from operation of the Shirco furnace pilot unit during the 18 month study period. The cost estimates in Table 23, however, are values furnished by Shirco, Inc. and are based on their assumptions for operation and maintenance of a 182 Kg/hr Shirco regeneration unit. The difference in the process costs in these two tables are mainly caused by varied value assumptions for carbon make-up, energy consumption, and maintenance materials, and operation and maintenance labor.

TABLE 20
Summary of Emissions From the Shirco-Carbon Regeneration System

	Afterburner Inlet	Afterburner Outlet	Scrubber Outlet
Flue Gas: Temperature, °F	1075	--	85
Velocity, ft/sec.	13.5	--	13.2
Static Pressure, in. H_2	- 0.25	--	±0.01
Flue Diameter, in.	4.	--	4.
Flue Area, sq. ft.	0.0873	--	0.0873
Gas Volume: CFM	70.7	--	69.1
SCFM	23.5	--	64.6
DSCFM	10.4	--	61.0
Water Vapor, % (by vol.)	55.8	--	5.6
Particulate Matter			
Sample Collection, grams	0.1604	--	0.0072
Sample Volume, DSCF	10.61	--	28.71
Concentration, grains/DSCF	0.2232	--	0.0039
Emission Rate, lbs/hour	0.021	--	0.0020
Ash, % of total	55.9	--	--
Sulfur Oxides (SO_x)			
Sulfur Dioxide (SO_2), ppm	636	--	0.4
Sulfates (as SO_2), ppm	14		0.2
Total (as SO_2), ppm	650		0.6
Emission Rate, lbs/hour (as SO_2)	0.068		0.0004
Free Sulfuric Acid (as SO_2), ppm	none detected		--
Nitrogen Oxides (NO_x)			
Concentration, ppm	134	53	21
	139	47	21
	126	44	21
	133	54	23
Average	133	50	22
Emission Rate, lbs/hour (as NO_2)	0.010		0.010
Orsat analysis (dry), CO_2, %	7.9	2.4	1.0
O_2, %	14.6	19.3	20.3
CO, %	0.0373	0.0047	0.0017
Hydrocarbon Analysis			
Carbon Monoxide (CO), ppm	373	47	17
Methane (CH_4), pm	<3	<3	<3
Hydrocarbons (as C_1)			
Gaseous	30	<10	<10
Condensable	526	127	13
Total HC (including CH_4)	556	127	13
Lbs/Hour (as C)	0.0110	--	0.0015

TABLE 21

Criteria and Unit Costs for Carbon Regeneration Cost Analysis

Criteria

1.	Plant flow, m^3/sec (MGD)	0.44	(10)
2.	Carbon dosage, g/m^3 (lb/MG)	75	(650)
3.	Carbon feed rate, kg/hr (lb/hr)	182	(400)
4.	Power consumption rate kWh/kg of carbon (kWh/lb carbon)		
	Shirco, Inc. estimate	2.6	(1.2)
	Pomona pilot unit estimate	3.7	(1.7)
5.	Labor, man-hr/kg of carbon (man-hr/lb of carbon)		
	Shirco, Inc. estimate	0.003	(0.0013)
	Pomona pilot unit estimate	0.006	(0.0025)

Unit Costs

1.	Carbon, cents/kg (cents/lb)	154	(70)
2.	Power, cents/ kWh	7	
3.	Water, cents/m^3 (cents/1000 gallons)	8	(30)
4/	Labor, $/man-hr	15	

Assumptions

1. Maintenance materials
   Shirco, Inc.: 5 percent of equipment cost/year
   Pomona pilot unit: 27 percent of equipment cost/year

2 Shipping and installation
   Shirco, Inc.,: 10 percent of equipment cost
   Pomona pilot unit: 25 percent of equipment cost

3. Initial engineering: 10 percent of equipment cost

4. Contingency
   Shirco, Inc.: 5 percent of equipment cost
   Pomona pilot unit: 10 percent of equipment cost

5. Amortization: 10 years at 10 percent interest rate

6. All assumptions are based on 6000 hours of operation/year

TABLE 22

Cost Estimates for the Shirco Furnace Based on Operation of the Pomona Pilot Plant

Capital	1000 of $	1000 of $	Cents/lb carbon
1. Equipment			
a. Carbon feed system	25		
b. Furnace system	345		
c. Air pollution control system	125		
TOTAL		495	
2. Shipping and Installation		124	
3. Engineering		49.5	
4. Contingency		49.5	
5. Total Capital Cost		718	
6. Capital Amortization			4.87
Operation and Maintenance			
1. Utilities			
a. Power			11.7
b. Water			0.135
2. Labor			3.75
3. Carbon make-up			4.9
4. Maintenance material			
a. Heating elements			4.16
b. Conveyor belt			1.187
c. Others			0.208
TOTAL PROCESS COST			30.91

TABLE 23.

Cost Estimates for the Shirco Furnace Based on Information Furnished by Shirco, Inc.

Capital	1000 of $	1000 of $	Cents/lb carbon
1. Equipment			
a. Carbon feed system	25		
b. Furnace system	345		
c. Air pollution control system	125		
TOTAL		495	
2. Shipping and Installation		45	
3. Engineering		50	
4. Contingency		25	
5. Total Capital Cost		615	
6. Capital Amortization			4.17
Operation and Maintenance			
1. Utilities			
a. Power			8.4
b. Water			0.135
2. Labor			1.875
3. Carbon make-up			3.5
4. Maintenance material			
a. Heating elements			0.52
b. Conveyor belt			0.396
c. Others			0.125
TOTAL PROCESS COST			19.12

As indicated in Table 21, Shirco, Inc. assumes 10 percent of total equipment cost for shipping and installation. The Shirco furnace and its components are shipped as separate units and are assembled at the site. This estimate also includes a concrete foundation for the entire unit and a shelter to protect the furnace and all its electrical units from rain. Judging from the time, labor and equipment which was utilized in the installation of the Pomona pilot unit and its extensive wiring, the estimate of 25 percent of total capital cost for shipping and installation seems to be more realistic. The difference for the power cost is due to power consumption per pound of carbon regenerated. Power consumption per pound of carbon was found to be 1.7 kWh with the pilot unit as opposed to a power consumption of 1.2 kWh claimed by Shirco, Inc. It should be noted, however, that a furnace larger than the pilot unit might be more efficient. This observation has been made comparing the pilot multiple hearth furnace with a full scale multiple hearth furnace which is used at the Pomona Water Reclamation Plant. The price difference of 1.4 cents per pound of carbon for makeup carbon is the result of 7 and 5 percent carbon losses in the Pomona pilot unit and the unit used by Shirco, Inc., respectively.

The major difference in the process costs in Tables 22 and 23 is caused by varied assumptions for heating elements and conveyor belt life expectancy. Shirco, Inc. claims 6000 hours of operation before these units need to be replaced. Based on the operation of the Pomona pilot unit, however, the average life of the heating elements was 750 hours and the conveyor belt had to be replaced after 1800 hours of operation. The difference in cost of labor in Table 21 arises from an assumption of 3000 man hours per year of operation as claimed by Shirco, Inc., and 6000 man hours predicted by Los Angeles County Sanitation Districts based on the operation of the Shirco pilot unit. Additional assumptions used for the preparation of the two cost estimates are explained in Table 21.

Cost Comparison

The total capital cost for the Shirco regeneration furnace was lower than that for the multiple hearth and higher than that for the the rotary kiln furnace. The study, however, indicates that the total process cost or operation and maintenance costs for the Shirco furnace is higher than those for both multiple hearth and rotary kiln furnaces. These findings are based on a report published by the U.S. Environmental Protection Agency [7] containing a cost comparison between the multiple hearth and the rotary kiln furnace. The engineers in charge of the previous furnace studies were consulted concerning ease of operation and required maintenance. In addition, representatives of the furnace companies were also consulted for the current cost of their carbon regeneration unit.

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